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ORDINARY MEETING.

9 November, 1937.

SYDNEY BRYAN DONKIN, President, in the Chair.

The President reported that, consequent upon the death of Lord Rutherford, an Honorary Member of The Institution, the following resolution had been passed by the Council :—

> "That the Council record the deep regret with which they have learned of the death of the Right Hon. Lord Rutherford, O.M., D.Sc., F.R.S., who was elected an Honorary Member of The Institution in April, 1928, in recognition of his great achievements in the field of physical science, and that an expression of the Council's sincere sympathy be conveyed to his family in their bereavement."

The Council reported that they had recently transferred to the class of

Members.

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Jack Leslie Wheeler.
Lawson Scott White.
Charles Arthur Wilson.

And had admitted as

Students.

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George Allan.
Harry Edwin Allison.
Dennis Ferguson Anderson.
John Frederick Collett Andrews.
Randolph Caldecott Anthony.
Krishnaji Vasudeo Apte, B.E. (*Bombay*).
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Henry French.
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Nicol Campbell Gillies.
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Alfred Ross.
David Ross.
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Vernon Gerald Walker, B.Sc. (*Birmingham*).
Donald Watson.
John Garth Watson.
Gladwin Westwood.
Geoffrey Owen White.
Reginald John Wilkinson.
William Brown Wilkinson.
William Donald Wilkinson, B.A., B.A.I. (*Dubl.*).
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Ronald Williams.
George Frederick Willment.
Edward Frank Newing Willson.
James Bruce Wilson, B.Sc. (*New Zealand*).
John Hunter Wilson.
Lindsay Arthur Wince.
John Norman Campbell Wood.
Reginald John Leonard Wood.
Malcolm James Wootton.
Richard Anthony Merle Wright.
Robert Halley Wyllie.

The following Paper was submitted for discussion, and, on the motion of the President, the thanks of The Institution were accorded to the Author.

Paper No. 5148.

"Combustion-Efficiencies of Gas and Oil Engines." †

By William Alfred Tookey, M. Inst. C.E.

TABLE OF CONTENTS.

Introduction.

For more than 25 years the Author has had the opportunity of observing the performances of gas engines in industrial service—mainly throughout South London but also in the West Midlands and the north-western districts of England. In the majority of instances, the power-output of the engine has been computed from indicator-diagrams and the latter have been used in order to diagnose faults and to estimate the effects of "tuning-up" to correct erratic working due to mechanical defects, to incorrect valve-timing, or to deranged ignition settings, as occasioned by mishandling, by uncorrected effects of wear, by unsuitable proportioning of air and gas, and by restrictions either in the induction-passages for gas and air or in exhaust-gas connexions.

It will be realized that unexpected problems had to be solved in this work, not the least of which was the design of an indicator reducing-gear which had to be capable of application to every type of industrial single-cylinder engine whatever the length of stroke. Furthermore, the gear had to combine reasonably accurate reproduction of piston movement with light weight—an essential requirement from a personal point of view. The type of gear ultimately found to combine universality of application with portability, simplicity, and reasonable accuracy is described and illustrated in the Appendix.

A further problem was to decide upon a basis of comparison which would permit the computation of mean pressure, from the plani-

† Correspondence on this Paper can be accepted until the 15th March, 1938.—Acting Sec. Inst. C.E.

metered area of indicator-diagrams, to be correlated with gas-meter readings. With the very many types and sizes of engines met with in all stages of repair and disrepair, the usual statement of cubic feet per indicated h.p.-hour (based on cylinder dimensions and number of impulses per unit time) gave no useful comparison of performance. It was found, however, that when the indicator mean pressure was taken as a fundamental unit representing power-output, and the rate of fuel-consumption, computed from the gas-meter readings, was expressed in terms of B.Th.U. per cubic foot of total cylinder volume (piston-displacement + clearance-volume), the factor obtained by dividing mean pressure by mixture-strength gave a direct indication of thermal efficiency. This factor was first used by the Author in 1909,[1] when he showed the advantage of this method of comparison in a critical analysis of the tests reported by the late Professor F. W. Burstall.[2] The method of comparison was further explained in a Paper read by the Author in January, 1914.[3] During the 23 years intervening, the general utility of the method has been well proved and the performance of every type of internal-combustion engine, when appraised upon this common basis, has brought to light various points of interest, some of which it is the object of this Paper to present and discuss.

The total cylinder-volume is in a sense a measure of the maximum air-capacity at normal temperature and pressure per cylinder per impulse. The air-capacity of an engine cylinder decides the limit of its ultimate power, as the fuel, whatever its nature, merely provides the wherewithal to burn the oxygen contained in the air. The Author has found that engine attendants, having been misled by nomenclature, are prone to decide that a gas engine must necessarily require manipulation of the gas-regulating cock more or less according to the load, not realizing that there is a minimum and a maximum limit of combustibility, and, indeed, a very definite ratio of gas to air which gives maximum combustion-efficiency. It is the air-content that matters most.

In hundreds of gas- and oil-power installations—particularly those erected in pre-war days—those responsible for the lay-out have stultified the good working qualities of the engine by placing the exhaust-silencer close to the cylinder instead of, say, 12 or more feet away. The kinetic energy of the waste gases leaving the cylinder

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[1] "The Influence of Compression Pressure upon Thermal Efficiencies of Gas-Engines." *Engineering*, vol. lxxxviii (1909), p. 522.

[2] Third Report to the Gas-Engine Research Committee. Proc. Inst.Mech.E., 1908 (Part 1), p. 5.

[3] "Commercial Tests of Internal-Combustion Engines," *Ibid.*, 1914 (Part 1), p. 5.

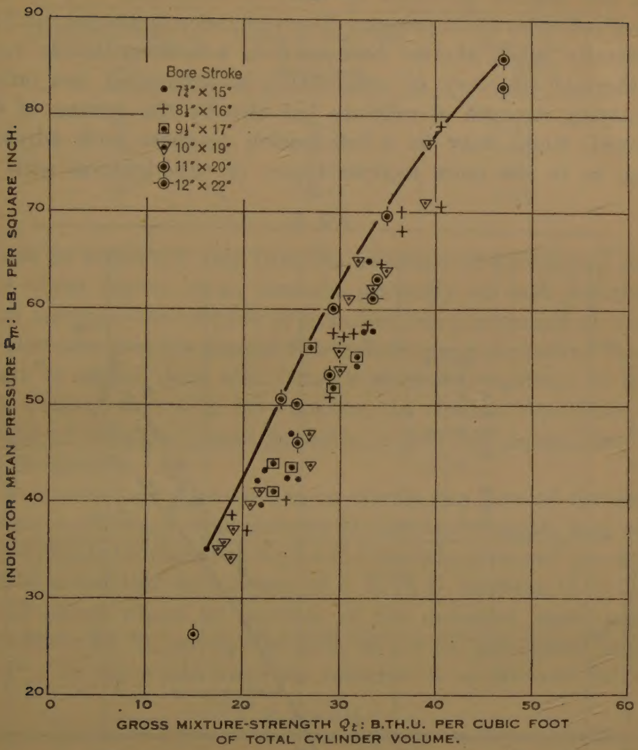
is entirely lost when the exhaust-box is too close; when it is at a greater distance, the spent gases continue to flow at considerable velocity from the cylinder and, with the normal overlap in valve-timing, fresh air is then induced to follow through, scavenging the combustion-chamber and ensuring good combustion-conditions for the next charge. It is evident that old doctrines need new preachers, for it has apparently been forgotten that the James Atkinson scavenging engine of 1892 functioned with a definite length of exhaust-pipe before release to an expansion-chamber. Incidentally, the Author has upon occasion criticized principals of technical colleges who arrange exhaust-gas calorimeters in research laboratories as close to the engine cylinder as is practicable. They may have good reasons from a tutorial point of view, but they fail to realize that in such a position considerable back-pressure is set up, with consequent retention of heated exhaust-products within the combustion-chamber. This seriously affects the efficiency of combustion, and also considerably restricts the mean effective pressure that would otherwise be obtainable when full charges of cool air refill the cylinder.

Relation of Mean Pressure to Mixture-Strength.

It would be wearisome to report at length the variations of the "work output ÷ heat input" (or mean pressure ÷ mixture-strength) factor noted in a multiplicity of tests made by the Author under industrial conditions, and to describe how and to what extent improvements have been possible by simple adjustments. Attention may, however, be directed to a few graphs which epitomize many tests.

Fig. 1 reproduces the observed performances under industrial conditions of a considerable number of single-cylinder horizontal gas engines of various sizes, all throttle-governed and with low-tension magneto-ignition. The cylinder-dimensions of the individual engines are indicated. It will be observed that the plotted points arrange themselves within well-defined limits from a minimum mixture-strength of 17 to 19 B.Th.U. (gross) per cubic foot to a maximum of 40 B.Th.U. per cubic foot with only four points beyond—these indicating merely that the normal industrial loads were usually well within the maximum or rated loads. An analysis of the plotted points along the line representing the better performances shows that a mixture-strength of 20 B.Th.U. per cubic foot of total cylinder volume produces an indicated mean effective pressure of 42·5 lb. per square inch, giving a factor of 2·125 lb. per square inch output

Fig. 1.



INDUSTRIAL PERFORMANCES OF THROTTLE-GOVERNED GAS ENGINES WITH LOW-TENSION MAGNETO-IGNITION.

per B.Th.U. input; taking intervals of 5 B.Th.U., Table I can be made for the higher efficiencies as marked by the line :—

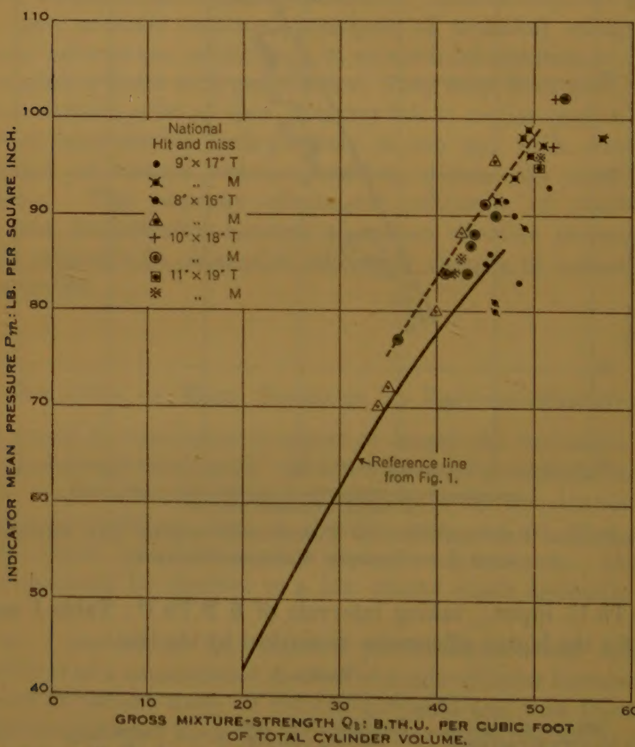
TABLE I.

Mixture-strength Q_t: B.Th.U. per cubic foot.	Indicator mean pressure P_m: lb. per square inch.	Factor T_m $(=P_m/Q_t)$.
20	42·5	2·12
25	52·0	2·08
30	61·0	2·03
35	69·5	1·98
40	77·5	1·94

From this it will be observed that with increasing mixture-strength the thermal efficiency of engine performance in terms of indicator mean pressure is decreased.

For gas engines governed by the "hit-and-miss" method, the range of indicator mean pressure observed under industrial conditions is naturally much shorter because it is not intentionally varied. The thermal efficiency of combustion is influenced not only by the varying strength of mixture but also by the system of firing employed, which may be a low-tension magneto with adjustable timing, as in the more modern types, or tube-ignition with non-

Fig. 2.



Industrial Performances of Hit-and-Miss Governed Gas Engines with Hot-Tube (T) and Magneto (M) Ignition.

adjustable timing, as fitted to engines of, say, 30 years ago. *Fig. 2* shows the relation between mixture-strength and indicator mean pressure for four sizes of cylinder, all by one manufacturer, and the plotted points discriminate between the various cylinder-sizes and types of ignition. Here again it will be observed that under industrial conditions there is a similar degree of dispersion of plotted points; the results for the higher efficiencies as indicated by the dotted line are given in Table II.

TABLE II.

Mixture-strength Q_t: B.Th.U. per cubic foot.	Indicator mean pressure P_m : lb. per square inch.	Factor T_m ($=P_m/Q_t$).
35	75·5	2·15
40	83·5	2·09
45	91·0	2·02
50	98·0	1·96

It will be noted not only that the incidence of scavenging strokes brings about higher mean pressure generally at each impulse for normal loading—the number of impulses being governed to suit the load—but also that the general thermal efficiency per unit of mixture-strength is higher than with throttle-governed engines. It is also clearly evident that with tube-ignition the combustion-efficiency on the basis of indicator mean pressure is definitely lower than with magneto-ignition.

It is interesting to analyse more closely the rate of decrease of combustion-efficiency with increase of mixture-strength, and, taking the best results tabulated above for the throttle-governed gas engines, it will be noted that an increase of 5 B.Th.U. between $Q_t = 20$ and $Q_t = 25$ brings about an increase of the indicator mean pressure from 42·5 to 52 lb. per square inch, or 1·9 lb. per square inch per B.Th.U.; for the whole range the variation is as given in Table III.

TABLE III.

Q_t: B.Th.U. per cubic foot.	Throttle-governed.			Hit-and-miss governed.		
	P_m : lb. per square inch.	Difference of P_m.	Difference-factor:	P_m : lb. per square inch.	Difference of P_m.	Difference-factor:
Col. (1)	Col. (2)	Col. (3)	Col. (3) ÷ 5	Col. (4)	Col. (5)	Col. (5) ÷ 5
20–25	42·5–52·0	9·5	1·9			
25–30	52·0–61·0	9·0	1·8			
30–35	61·0–69·5	8·5	1·7			
35–40	69·5–77·5	8·0	1·6	75·5–83·5	8·0	1·6
40–45	77·5–85·0	7·5	1·5	83·5–91·0	7·5	1·5
45–50				91·0–98·0	7·0	1·4

Comparing the above difference-factors with those previously tabulated, it becomes evident that a higher combustion-efficiency is attained with weaker mixtures—a conclusion which will be discussed later in the Paper.

It will be understood that in the tests of gas engines in industrial service it is impracticable to measure the volume of the combustion-space, but from indicator-diagrams the compression-pressure is

measured and this, with "light spring" cards to determine the volumetric efficiency, is sufficient to enable the designed volume-ratio to be estimated with a close approximation to accuracy. *Fig. 3* reproduces the chart used by the Author relating compression-pressures P_c (gauge) with cylinder volume-ratios r, the method of plotting being as indicated on the curves.

Fig. 3.

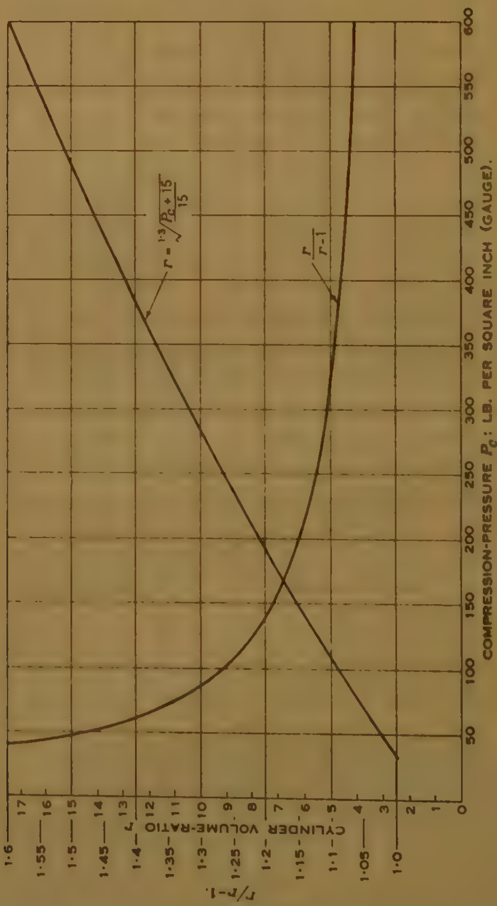


CHART CO-ORDINATING COMPRESSION-PRESSURE (GAUGE) WITH CYLINDER VOLUME-RATIO.

The relation between the indicated thermal efficiency E_m and the Tookey factor T_m is

$$E_m \times \frac{r}{r-1} \times 5{\cdot}4 = T_m ,$$

and Table IV, pp. 174–175, has been calculated to correlate T_m and

E_m for various values of r and for various values of $n-1$ in the air-standard efficiency formula $E_m = 1 - \left(\frac{1}{r}\right)^{n-1}$.

In the Tables of test results given below,

Q_t denotes the mixture-strength in B.Th.U. (gross) per cubic foot of total cylinder-volume (piston-displacement + clearance-volume);
P_m ,, indicator mean pressure;
P_n ,, brake mean effective pressure;
T_m ,, $P_m \div Q_t$;
T_n ,, $P_n \div Q_t$.

There is a temptation, when in possession of a number of test records of various types of gas engines, to reproduce a number of tabulated comparisons. The gas engine, however, is not now in the forefront of internal-combustion-engine development as it was 25 to 30 years ago. It will therefore suffice to record a few results only to represent the performances of multi-cylinder engines with various kinds of power-gases.

A four-cylinder two-crank vertical tandem gas engine with lower cylinders 17 inches and upper cylinders 18 inches bore, 18 inches stroke, $r = 6{\cdot}5$, running at 300 revolutions per minute with producer-gas when tested by the Author at the makers' works, gave results summarized in Table V.

TABLE V.

Q_t: B.Th.U. per cubic foot.	P_m: lb. per square inch.	P_n: lb. per square inch.	T_m $(=P_m/Q_t)$.	T_n $(=P_n/Q_t)$.
33·2	69·5	51·6	2·09	1·63
31·25	65·4	46·0	2·09	1·455
24·5	51·3	35·1	2·09	1·43
20·35	42·5	22·45	2·09	1·103
19·8	41·4	11·75	2·09	0·594
16·1	33·7	0	2·09	—

Equal value of T_m throughout was obtained in this case by suitably adjusting the timing of the high-tension ignition-device.

A two-cylinder four-cycle double-acting horizontal tandem gas engine with cylinders 33·46 inches bore, 43·3 inches stroke, $r = 6{\cdot}3$, running at 106 revolutions per minute with blast-furnace gas gave results as shown in Table VI (p. 176).

TABLE IV.—INDICATED THERMAL EFFICIENCY E_m AND TOOKEY

Volume-ratio r		4	5	6	7	8	9	10
$n-1$ 0·13	E_m	0·165	0·188	0·207	0·224	0·236	0·248	0·258
	T_m	1·187	1·27	1·34	1·41	1·455	1·505	1·543
0·14	E_m	0·176	0·201	0·222	0·240	0·252	0·265	0·275
	T_m	1·266	1·356	1·44	1·51	1·555	1·61	1·635
0·15	E_m	0·188	0·214	0·236	0·254	0·268	0·28	0·292
	T_m	1·354	1·445	1·53	1·60	1·655	1·70	1·735
0·16	E_m	0·198	0·226	0·25	0·267	0·282	0·297	0·308
	T_m	1·425	1·525	1·62	1·682	1·74	1·805	1·83
0·17	E_m	0·21	0·239	0·262	0·282	0·298	0·312	0·324
	T_m	1·51	1·61	1·70	1·775	1·84	1·895	1·925
0.18	E_m	0·221	0·251	0·275	0·295	0·312	0·327	0·339
	T_m	1·66	1·695	1·782	1·86	1·925	1·985	2·03
0·19	E_m	0·232	0·263	0·288	0·308	0·326	0·341	0·354
	T_m	1·67	1·775	1·865	1·94	2·01	2·07	2·125
0·20	E_m	0·242	0·275	0·301	0·322	0·34	0·355	0·369
	T_m	1·81	1·855	1·95	2·03	2·1	2·15	2·21
0·21	E_m	0·252	0·286	0·314	0·335	0·364	0·37	0·383
	T_m	1·812	1·94	2·035	2·11	2·245	2·25	2·295
0·22	E_m	0·263	0·298	0·325	0·348	0·367	0·383	0·397
	T_m	1·875	2·01	2·105	2·19	2·265	2·325	2·38
0·23	E_m	0·272	0·309	0·337	0·36	0·38	0·397	0·411
	T_m	1·956	2·087	2·19	2·27	2·345	2·41	2·463
0·24	E_m	0·283	0·32	0·349	0·373	0·392	0·411	0·424
	T_m	2·03	2·16	2·265	2·35	2·42	2·49	2·54
0·25	E_m	0·293	0·331	0·36	0·385	0·405	0·423	0·437
	T_m	2·1	2·24	2·335	2·43	2·5	2·57	2·62
0·26	E_m	0·303	0·342	0·374	0·397	0·42	0·435	0·45
	T_m	2·17	2·31	2·425	2·52	2·59	2·64	2·695
0·27	E_m	0·312	0·352	0·382	0·408	0·43	0·448	0·463
	T_m	2·245	2·38	2·475	2·57	2·65	2·73	2·77
0·28	E_m	0·322	0·363	0·395	0·420	0·442	0·460	0·475
	T_m	2·30	2·45	2·56	2·65	2·73	2·795	2·82
0·30	E_m	0·34	0·38	0·415	0·44	0·46	0·48	0·50
	T_m	2·44	2·57	2·69	2·77	2·84	2·92	2·97

Factor T_m for Various Values of r and $n-1$.

11	12	13	14	15	16	18	20
0·268 1·59	0·275 1·62	0·284 1·66	0·293 1·705	0·297 1·715	0·302 1·74	0·312 1·785	0·322 1·83
0·285 1·69	0·294 1·73	0·302 1·765	0·308 1·79	0·315 1·805	0·322 1·85	0·333 1·905	0·342 1·945
0·303 1·80	0·311 1·83	0·319 1·865	0·327 1·90	0·334 1·915	0·340 1·956	0·351 2·01	0·362 2·06
0·319 1·895	0·328 1·93	0·336 1·965	0·345 2·0	0·351 2·01	0·358 2·06	0·370 2·12	0·380 2·16
0·334 1·985	0·345 2·03	0·354 2·07	0·361 2·10	0·369 2·115	0·376 2·16	0·388 2·22	0·397 2·26
0·35 2·075	0·36 2·12	0·37 2·165	0·378 2·2	0·385 2·225	0·393 2·26	0·405 2·315	0·416 2·365
0·366 2·175	0·376 2·213	0·385 2·25	0·394 2·29	0·402 2·33	0·410 2·36	0·422 2·41	0·434 2·46
0·38 2·26	0·392 2·31	0·40 2·34	0·41 2·38	0·418 2·415	0·425 2·45	0·439 2·51	0·45 2·56
0·396 2·35	0·407 2·4	0·416 2·43	0·426 2·48	0·433 2·51	0·442 2·54	0·454 2·595	0·467 2·655
0·41 2·43	0·42 2·47	0·43 2·52	0·44 2·56	0·45 2·6	0·458 2·64	0·47 2·685	0·482 2·74
0·423 2·51	0·435 2·56	0·446 2·61	0·455 2·65	0·464 2·685	0·471 2·71	0·485 2·77	0·498 2·83
0·437 2·59	0·449 2·65	0·459 2·685	0·470 2·73	0·478 2·77	0·485 2·79	0·501 2·86	0·572 2·91
0·45 2·67	0·462 2·72	0·473 2·77	0·483 2·81	0·492 2·84	0·50 2·88	0·514 2·94	0·528 3·0
0·463 2·75	0·475 2·8	0·487 2·85	0·496 2·88	0·505 2·92	0·513 2·96	0·528 3·02	0·54 3·07
0·476 2·815	0·488 2·87	0·499 2·92	0·51 2·96	0·519 3·0	0·526 3·03	0·541 3·1	0·555 3·15
0·4885 2·9	0·50 2·945	0·512 3·0	0·522 3·04	0·531 3·07	0·54 3·11	0·554 3·165	0·567 3·225
0·573 3·05	0·525 3·09	0·536 3·135	0·547 3·2	0·556 3·21	0·564 3·25	0·579 3·31	0·59 3·35

TABLE VI.

Q_t : B.Th.U. per cubic foot.	P_m : lb. per square inch.	P_n : lb. per square inch.	T_m $(=P_m/Q_t)$.	T_n $(=P_n/Q_t)$.
37·8	75·3	62·6	1·99	1·665
37·4	73·1	60·4	1·955	1·615
37·8	71·4	58·6	1·89	1·55
36·1	68·7	54·3	1·904	1·504
33·1	60·0	45·6	1·813	1·377
24·1	42·5	29·3	1·762	1·215
18·6	31·0	14·7	1·665	0·79

A four-cylinder vertical four-crank gas engine with cylinders 12 inches bore, 11 inches stroke, $r = 5{\cdot}0$, running at 428 revolutions per minute with coal gas (town supply) gave results as shown in Table VII.

TABLE VII.

Q_t (gross) : B.Th.U. per cubic foot.	P_m : lb. per square inch.	P_n : lb. per square inch.	T_m $(=P_m/Q_t)$.	T_n $=(P_n/Q_t)$.
40·5	85·0	63·4	2·10	1·564
36·3	76·6	56·1	2·11	1·545
30·0	62·4	41·6	2·08	1·386
24·0	46·6	29·0	1·933	1·208
20·15	38·0	15·0	1·885	0·747

It will be seen from the above that, as the practicable minimum mixture-strength is approached, the thermal efficiency on the basis of indicated h.p. deteriorates rapidly with normal governing methods and without advancement of ignition to suit the weaker mixtures. On the other hand, with what might be called automobile methods (where the governor works on a throttle to reduce the charge but with a carburettor in which, with lowering of induction-pressure consequent upon throttling, the gas inlet aperture is caused to open slightly and thus to increase the ratio of gas to air), the minimum practicable mixture-strength is lower, as the following comparison (Table VIII) shows. That Table gives the results of tests on a four-cylinder engine of 4½ inches bore and 6 inches stroke, which gave 24 brake h.p. output when running at 1,000 revolutions per minute. It was direct-coupled to a 15-kilowatt direct-current dynamo, the output of which was absorbed by water resistances. The brake h.p. and the brake mean effective pressure (P_n) were computed from the dynamo-makers' efficiency figures for converting kilowatts to brake h.p.

From the graph (*Fig. 4*, p. 178) it will be observed that at low loads with normal control misfiring has occurred because with weak mixtures the separate cylinders are not equally supplied, but that when both

TABLE VIII.

Brake HP.	Q_t: B.Th.U. per cubic foot.	P_n: lb. per square inch.	T_n $(=P_n/Q_t)$.	P_m: lb. per square inch.	T_m $(=P_m/Q_t)$.
With normal governing and control of mixture					
21·5	41·8	53·1	1·27	77	1·84
24·1	44·5	59·2	1·33	83	1·86
25·85	41·8	63·8	1·525	88	2·10
25·85	43·0	63·8	1·48	88	2·05
22·4	39·8	55·4	1·39	80	2·01
22·4	40·4	55·4	1·37	80	1·98
17·3	37·4	42·7	1.14	67	1·79
16·75	37·4	41·4	1·105	66	1·765
11·87	34·7	29·3	0·844	53	1·53
11·87	33·6	29·3	0·872	53	1·58
6·7	29·8	16·55	0·556	40	1·34
With special control of mixture					
0	19·1	—	—	24	1·26
4·9	24·0	11·6	0·484	48	1·31
12·2	30·65	29·75	0·970	55	1·79
23·5	43·8	57·6	1·315	82	1·87

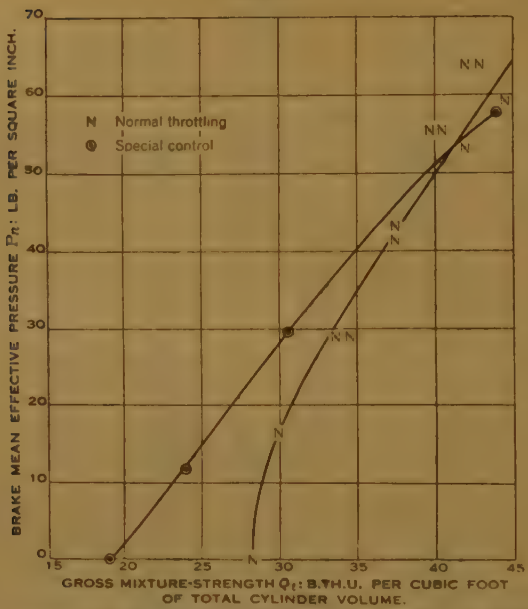
gas and air are automatically regulated by the governing mechanism, the mixtures have evidently been regularly fired, as combustion-efficiency at low loads has been better maintained.

COMPARISONS BETWEEN TESTS WITH MIXED AND UNMIXED GASES.

It is always of interest to compare industrial performances with the results of laboratory tests with mixed and unmixed gases. With this object in view, the Author has converted into terms of P_m and Q_t (Table IX, p. 178) the results of tests with carbon monoxide reported by Dr. Aubrey F. Burstall.[1] The engine was a single-cylinder variable-compression engine, and the test taken for comparison is that made at 1,000 revolutions per minute with a compression-ratio of 5. The P_m values were computed by noting the power required to motor the cylinder at speed, immediately after the test run, and adding the frictional mean pressure to the brake mean effective pressure. A similar series of trials with town gas was reported by Dr. Aubrey F.

[1] "Experiments on the Combustion of Carbon-Monoxide—Air Mixtures in a High-Speed Engine," Proc. Inst. Auto. Eng., vol. 21 (1926–27), p. 628.

Fig. 4.



IMPROVEMENT IN INDUSTRIAL RESULTS OBTAINED BY APPLYING AUTOMOBILE METHODS TO MIXTURE-PROPORTIONING.

TABLE IX.—TESTS WITH CARBON MONOXIDE AND AIR MIXTURE.

P_m : lb. per square inch.	Q_t : B.Th.U. per cubic foot.	Ignition advance : crank degrees.
85·8	41·2	91
92·0	44·0	76
92·3	43·4	63
94·6	48·5	71
95·6	49·0	57
96·1	49·8	57
98·6	50·0	66
111·0	61·0	45
116·0	64·0	39
116·5	65·0	32
120·5	69·0	30
115·0	73·5	41

Burstall [1] at the same speed and same compression-ratio, and the results have been similarly converted (Table X.). For town gas both gross and net calorific values are given.

[1] "Experiments on the Power and Efficiency of the High-Speed Gas Engine," *Ibid.*, vol. 19 (1924–25), p. 620.

Table X.—Tests with Coal Gas and Air Mixture.

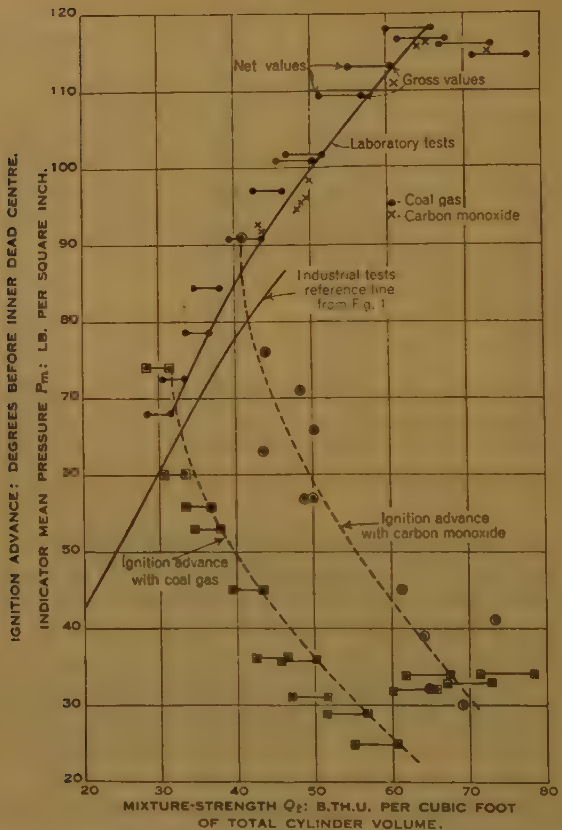
P_m : lb. per square inch.	Q_t : B.Th.U. per cubic foot.		Ignition advance : crank degrees.
	Gross.	Net.	
68·2	31·55	28·7	74
72·5	33·50	30·5	60
78·8	36·95	33·6	56
84·6	38·0	34·6	53
90·8	43·4	39·5	45
97·3	46·5	42·3	36
101·7	50·25	45·7	36
101·8	51·8	47·1	31
105·7	54·55	49·6	31
109·7	56·8	51·6	29
113·2	60·5	55·0	25
115·2	61·6	56·0	25
118·0	66·0	60·0	32
16·7	67·6	61·5	34
116·0	73·7	67·0	33
114·7	78·3	71·2	34

The graphs in *Fig. 5* (p. 180) show the relation between the Tables more clearly, and, in the case of town gas, the differences between gross and net values are shown by horizontal lines. Ignition-timing of gaseous mixtures is of great importance ; the curves formed by the plotted points for the angular degrees of advance for the two mixtures enable the difference in timing for practically equivalent mixture-strengths to be realized. The erratic variations of P_m in relation to ignition-timing shown in *Fig. 5* at the richer mixture-strengths denote that the latter have reached a critical stage.

It will be observed that for all practical purposes the gross calorific value of the mixed (coal) gas and the calorific value of the carbon monoxide give equivalent duties in terms of indicator mean pressure. Indeed, the difference is so very slight that the discrepancy from exact equivalence would suggest that the multipliers used in the calculation of calorific values may not have been quite correct. The difference in ignition-advance, however, is striking, a mixture-strength Q_t of, say, 41·5 of carbon monoxide and air requiring 91 angular degrees advance, as compared with only 48 angular degrees required for the coal-gas and air mixture containing hydrogen and hydrogen compounds.

In gas-engine practice no advance in combustion-efficiency has been made since Professors Bertram Hopkinson and F. W. Burstall reported the results of their independently-conducted researches in 1908 at Cambridge and at Birmingham respectively. *Fig. 6* (p. 181) has been prepared to demonstrate this fact. It will be evident that Dr.

Fig. 5.



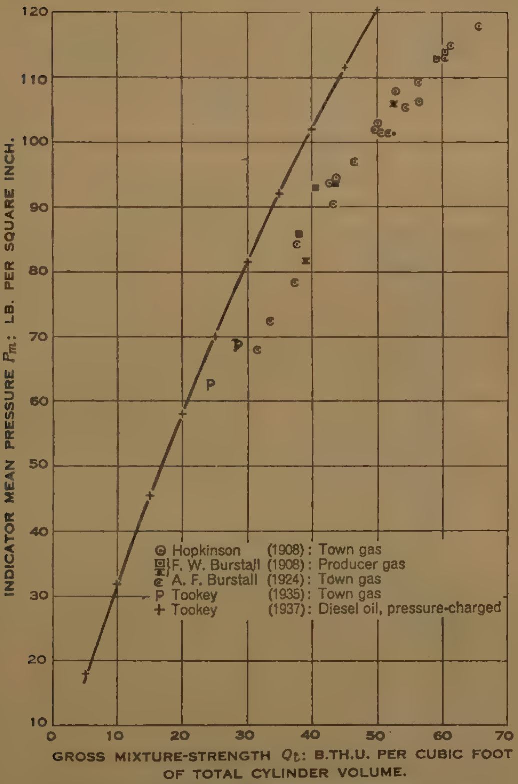
Equivalence of Coal Gas and Carbon Monoxide with Appropriate Ignition-Timing.

Aubrey Burstall's experiments in 1924 confirm the earlier results recorded by his father, and that later industrial trials made by the Author in 1935 are also in accord. In all these cases the compression volume-ratio is of the order of 5 or 5·5 to 1. It is interesting to realize that, whilst all the plotted points other than Dr. Aubrey Burstall's refer to medium-speed stationary engines, his figures referring to a single-cylinder engine at 1,000 revolutions per minute agree remarkably well with the others, particularly at the richer mixture-strengths.

Compression-Ignition Engines

It is well known that with higher values of r the efficiency of combustion in internal-combustion engines is increased, and that

Fig. 6.



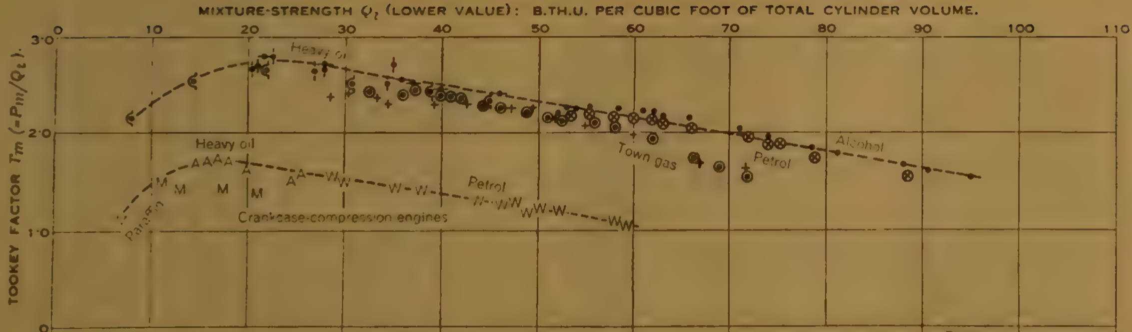
Correlation of Combustion-Efficiencies of Gas Engine and Compression-Ignition Engine.

heavy petroleum distillates when injected as in the diesel or compression-ignition type of construction enable full advantage to be taken with industrial success. The correlation of the efficiencies obtained with gas and with heavy liquid fuel is shown by the long curve in *Fig.* 6, which reproduces test results obtained by the Author with a modern 8-cylinder vis-a-vis horizontal oil engine with pressure-charging. The range of efficient combustion is greatly extended, particularly at the less rich end of the scale, whilst with the richer mixtures it will be observed that while the gas-engine performance gradually deteriorates, the compression-ignition engine maintains its efficiency in a conspicuous manner.

A further chart (*Fig.* 7, p. 182) is reproduced from a Paper read by the Author[1] in 1926. It correlates the gas-engine performances with

[1] "Industrial Tests of Internal-Combustion Engines." Diesel Engine Users' Association, Publication S. 70. 9 April, 1926.

Fig. 7.

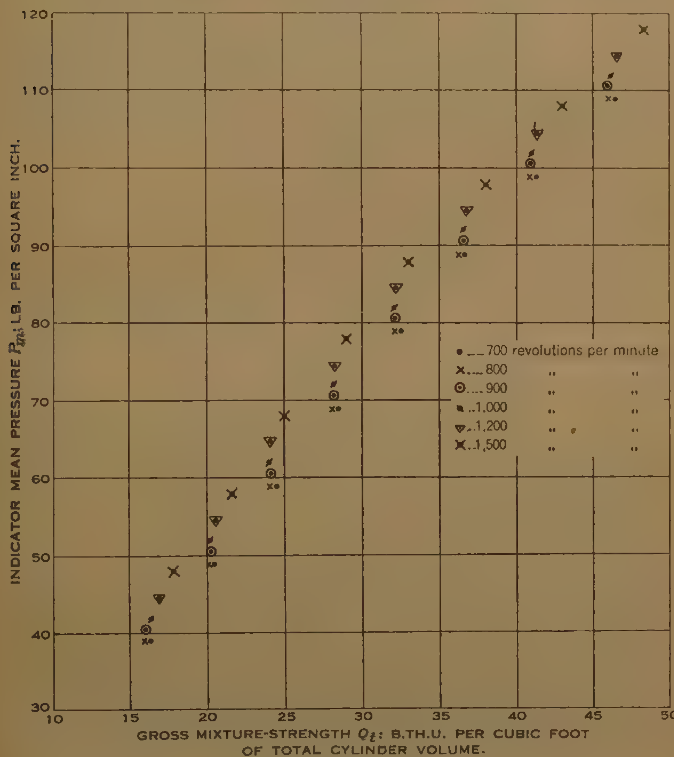


Fuel	Type	Brake H.-P.	N° of cylinders	Cycle	Revolutions per minute	Authority	Reference	Piston-displacement: cubic feet	Compression volume-ratio
Heavy Oils	Nobel diesel	1600	4	2-stroke	65 & 85	Roseborg	"Engineer" 3.2.22	11·62	14
					100	"			
	Blackstone	250	3	4 "	230	Chaloner	Makers, 12.2.25	2·05	9
Gas	Variable-compression research engine		1	4 "	1000	Burstall, A.F.	Proc.I.Auto.E. Vol. XIX (1924)		5
Petrol					1400	"	" p. 174 Vol. XVIII		
Alcohol			1	4 "	1500	Ricardo	(1923)		5
						"	" p. 190		
Crankcase-compression type									
Paraffin	M. Mietz & Weiss	15	1	2 "	290	Weinburgh	Cornell University (1904)	0·55	5
Heavy oil	A. Allen	25	1	2 "	375	Allcutt	Proc. I.Mech.E. (1925)	0·45	5·8
Petrol	W. Day		1	2 "	1200	Watson	" Auto.E. (1910)		3·9

THE EFFECT OF MIXTURE-STRENGTH VARIATION UPON THE VALUE OF P_m/Q_t.

those of various liquid-fuel engines, and enables the relative limits of combustion-efficiency of gas engines, petrol engines and heavy-oil engines to be appreciated. The petrol-engine performances have been plotted from the Empire Motor Fuels Report.[1] The vertical scale

Fig. 8.



Tookey Factor Values.

Revs. per min.							
700–800	2·40	2·425	2·42	2·43	2·43	2·41	2·37
900	2·50	2·50	2·50	2·50	2·50	2·475	2·42
1000	2·60	2·57	2·56	2·565	2·53	2·50	2·445
1200	2·66	2·625	2·62	2·62	2·59	2·55	2·49
1500	2·73	2·70	2·70	2·66	2·63	2·55	2·53

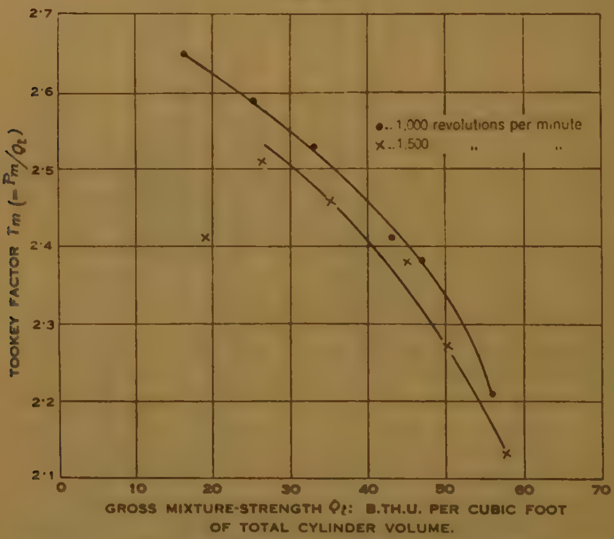
The Influence of Speed upon the Performance of Compression-Ignition Engines.

is the Tookey factor (indicator mean pressure ÷ mixture-strength), and it will be obvious that high performance on the basis of indicator mean pressure cannot be combined with the highest possible combustion-efficiencies.

[1] Proc. Inst. Auto. Eng., vol. 18, Part I (1923–4).

During recent years a considerable amount of development-work has been undertaken with high-speed compression-ignition engines, and it is interesting to determine to what extent combustion-efficiency is affected by increasing rotational speeds. *Fig. 8* (p. 183) has been prepared from a series of tests made with a Paxman-Ricardo four-cylinder compression-ignition engine and shows the relation between the indicator mean pressure P_m (computed from the brake mean effective pressure P_n, and the ascertained frictional resistances at the various speeds) and the mixture-strength Q_t. From *Fig. 8* it will be observed that speeds of 700 and 800 revolutions per minute

Fig. 9.



Influence of Speed upon Combustion-Efficiency with Injection-Timing Unaltered.

give combustion-efficiencies of practical equivalence, and a similar merging is to be detected at speeds of 1,200 and 1,500 revolutions per minute when P_m is above 100 and Q_t above 40. The variations in the value of T_m are tabulated for each speed at the base of the chart, and it will be apparent that good tuning has in this instance equalized the higher efficiencies at the higher speeds.

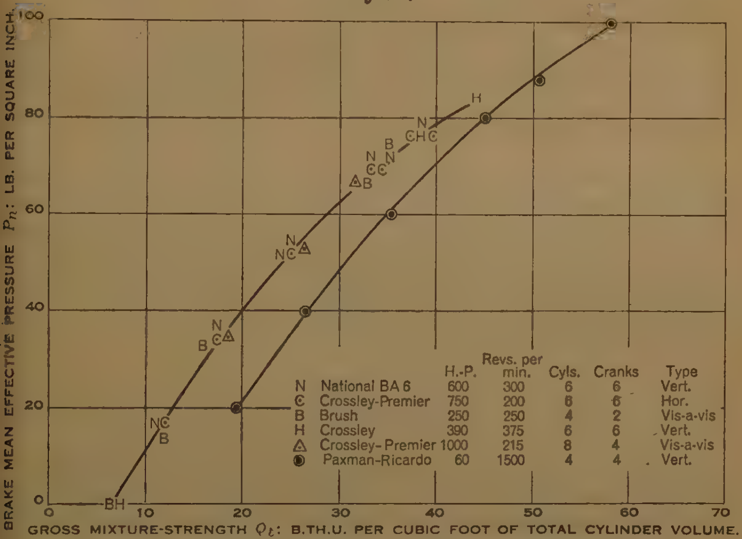
The difference in combustion-efficiency brought about by liquid-fuel injection-timing favouring a speed of 1,000 revolutions per minute and not so well suiting 1,500 revolutions per minute is shown in *Fig. 9*, which reproduces the test-results of another engine of the same type (Paxman-Ricardo) tested by the Author. The lag of

ignition consequent upon cooler cylinder-conditions at light load—starting from cold—is particularly to be noted.

Fig. 10 has been plotted to show the difference in performance on the basis of mixture-strength between the high-speed type of compression-ignition engine previously referred to in *Fig. 9* and the ordinary heavy normal-speed types suitable for industrial service. In *Fig. 10*, however, the vertical scale is P_n (brake mean effective pressure) instead of P_m (indicator mean pressure).

It will be seen that, whilst five very dissimilar heavy-oil engines give practically identical results, the high-speed engine, in consequence

Fig. 10.



Comparative Performances of Normal and High-Speed Stationary Compression-Ignition Engines.

of its lower mechanical efficiency due to greater losses in fluid and other resistances, falls short in comparison; its range of practical mean pressures, however, is more extensive, due no doubt to the improved pumping efficiency, or, in other words, the increase in volumetric efficiency due to the ramming effect of the kinetic energy imparted to the entering charge of air.

Evaluating the mean curves for both the normal industrial engines and the high-speed type, Table XI (p. 186) shows the increase in mean pressure developed for each additional 5 B.Th.U. per cubic foot in mixture-strength. This comparative Table shows that as heat-engines both types are capable of thermal efficiencies of the same order.

TABLE XI.

Industrial type.					High-speed type.				
Q_t: B.Th.U. per cubic foot.	P_n: lb. per square inch.	Differences of		Difference-factor:	Q_t: B.Th.U. per cubic foot.	P_n: lb. per square inch.	Differences of		Difference-factor:
		Q_t.	P_n.				Q_t.	P_n.	
Col. (1)	Col. (2)	Col. (3)	Col. (4)	Col. (4) ÷ Col. (3)	Col. (5)	Col. (6)	Col. (7)	Col. (8)	Col. (8) ÷ Col. (7).
10	12	—	—	—	10	—	—	—	—
15	26	5	14	2·8	15	—	—	—	—
20	39	5	13	2·6	20	23	—	—	—
25	51	5	12	2·4	25	36	5	13	2·6
30	62	5	11	2·2	30	48	5	12	2·4
35	72	5	10	2·0	35	60	5	12	2·4
40	82	5	10	2·0	40	70	5	10	2·0
					45	80	5	10	2·0
					50	88	5	8	1·6
					55	95	5	7	1·4

Fig. 11 shows the comparative performances of an atmospherically-charged engine and of a similar engine by the same constructors, but pressure-charged by a blower driven by the engine's own power and therefore comparable as to P_n (brake mean effective pressure). Evaluating the curve in a similar manner to that adopted in connexion with *Fig. 10*, Table XII has been prepared.

TABLE XII.

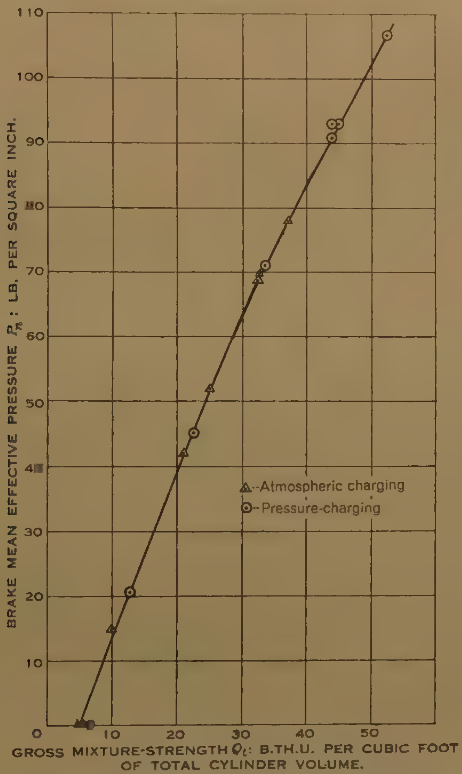
Q_t: B.Th.U. per cubic foot. Col. (1)	P_n: lb. per square inch. Col. (2)	Differences of		Difference-factor: Col. (4) ÷ Col. (3)
		Q_t. Col. (3)	P_n. Col. (4)	
5	nil	—	—	—
10	14·0	5	14	2·8
15	27·5	5	13·5	2·7
20	40	5	12·5	2·5
25	52	5	12	2·4
30	63·5	5	11·5	2·3
35	74	5	10·5	2·1
40	84	5	10	2·0
45	93·5	5	9·5	1·9
50	102·5	5	9	1·8

This again shows that equivalence in the rate of decrease of thermal efficiency follows the steps of 5 B.Th.U. increase in the mixture-strength Q_t.

Fig. 12 (p. 188) has been prepared from the results of a test conducted at Greenock, in the presence of the Author as a member of the

Marine Oil-Engine Trials Committee of the Institution of Mechanical Engineers. It refers to the six-cylinder Scott marine engine, 2,750 brake h.p. at 138 revolutions per minute, for M.S. *Polyphemus*, working pressure-charged on the Büchi system, as reported in the sixth report of that committee.[1] The performances then noted were

Fig. 11.



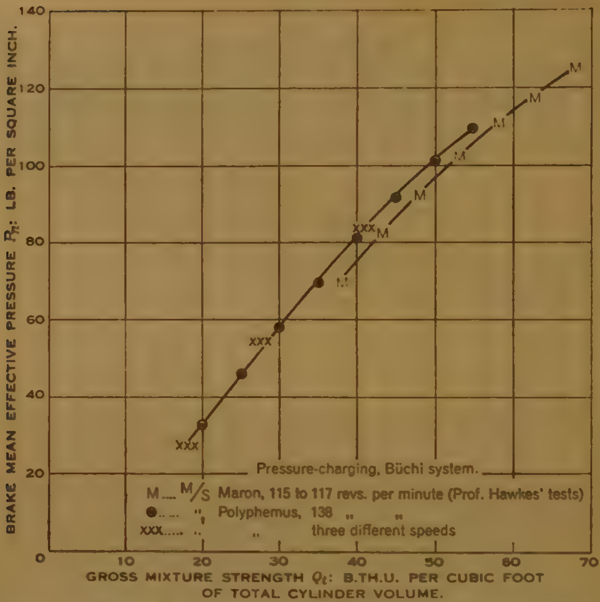
COMPARISON OF PERFORMANCES OF SIX–CYLINDER COMPRESSION-IGNITION ENGINE WITH ATMOSPHERIC AND PRESSURE CHARGING.

in close agreement with those of a similar engine built by the North-Eastern Marine Co. for M.S. *Maron* when tested and reported upon by Professor C. J. Hawkes [2]; as a matter of interest his results are also shown on *Fig. 12.* Evaluation of the curve enables the change in thermal efficiency due to change in mixture-strength to be demonstrated as in Table XIII.

[1] Proc. Inst. Mech. E., vol. 121 (1931), p. 183.

[2] "The Oil Engines of the Motorship *Maron*." *The Shipbuilder*, March, 1930.

Fig. 12.



PERFORMANCES OF PRESSURE-CHARGED COMPRESSION-IGNITION MARINE ENGINES.

TABLE XIII.

Polyphemus.					*Maron.*				
Q_t: B.Th.U. per cubic foot.	P_n: lb. per square inch.	Differences of		Difference-factor:	Q_t: B.Th.U. per cubic foot.	P_n: lb. per square inch.	Differences of		Difference-factor:
		Q_t.	P_n.				Q_t.	P_n.	
Col. (1)	Col. (2)	Col. (3)	Col. (4)	Col. (4) ÷ Col. (3)	Col. (5)	Col. (6)	Col. (7)	Col. (8)	Col. (8) ÷ Col. (7)
20	33	5	—	—					
25	46	5	13	2·6					
30	58	5	12	2·4					
35	70	5	12	2·4	38	70	—	—	—
40	81·5	5	11·5	2·3	43	82	5	12	2·4
45	92	5	10·5	2·1	48	93	5	11	2·2
50	101·5	5	9·5	1·9	53	102·5	5	9·5	1·9
55	110	5	8·5	1·7	58	111	5	8·5	1·7
					63	118·5	5	7·5	1·5
					68	125	5	6·5	1·3

From *Fig. 11* and Table XII, which may be taken as representing normal performances of well-constructed and properly-tuned compression-ignition engines, it is possible to appraise the depreciat-

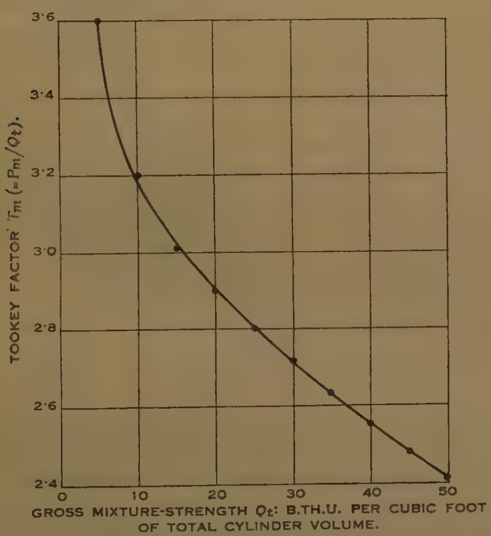
ing value of $n - 1$ in the air-standard efficiency-formula over the whole range of practicable mixture-strength. This has been calculated in Table XIV.

TABLE XIV.—EVALUATION OF $n-1$ FOR STEPS OF 5 B.TH.U. IN MIXTURE-STRENGTH.

Q_t : B.Th.U. per cubic foot.	Difference-factor (from Table XII).	$n-1$.
5–10	2·8	0·26
10–15	2·7	0·25
15–20	2·5	0·225
20–25	2·4	0·21
25–30	2·3	0·20
30–35	2·1	0·18
35–40	2·0	0·17
40–45	1·9	0·16
45–50	1·8	0·15

In the same engine to which *Fig. 11* refers, the frictional resistances —fluid and mechanical—were determined by computation as equiva-

Fig. 13.



RATIOS OF INDICATOR MEAN PRESSURE AND MIXTURE-STRENGTH CORRESPONDING TO *Fig. 11.*

lent to 18 lb. per square inch. Adding this figure to the values of P_n noted and plotted on *Fig. 11*, the indicator mean pressure P_m is obtained, and *Fig. 13* has been prepared showing T_m in terms

of Q_t. From the corresponding readings along the mean curve for steps of 5 B.Th.U. in mixture-strength, Table XV shows the corresponding values of E_m (indicated thermal efficiency on the gross calorific value) and of $n - 1$.

TABLE XV.

Q_t: B.Th.U. per cubic foot.	P_n: lb. per square inch.	P_m: lb. per square inch.	T_m: $(=P_m/Q_t)$.	Indicated thermal efficiency.	$n - 1$.
0	—	—	—	0·63	0·40
5	0	18	3·6	0·612	0·381
10	14	32	3·2	0·544	0·316
15	27·5	45·5	3·01	0·512	0·289
20	40	58	2·9	0·493	0·273
25	52	70	2·8	0·476	0·26
30	63·5	81·5	2·72	0·462	0·247
35	74	92	2·63	0·447	0·236
40	84	102	2·55	0·433	0·227
45	93·5	111·5	2·48	0·422	0·218
50	102·5	120·5	2·41	0·41	0·21

In the air-standard efficiency-formula the ratio of specific heats $n = 1{\cdot}40$. Messrs. H. T. Tizard and D. R. Pye in the Empire Motor Fuels Committee report [1] gave $n - 1 = 0{\cdot}258$ for correct mixtures and 0·296 for 20-per-cent.-weak mixtures as corresponding to the maximum observed efficiencies with carburettor-type engines.

It will be seen that at no load with the very weak mixtures that are practicable in compression-ignition engines, the air-standard efficiency-value of $n - 1$ is approached within 95 per cent., but that for normal rated loads with $Q_t = 35$, the actual efficiency is only 71 per cent. of the air-cycle standard. The latter figure is similar to that which the late Sir Dugald Clerk, M. Inst. C.E., reported as a result of his well-known researches in connexion with the working fluid of internal-combustion engines, and it is also in accordance with the "Note on the Practical Application of the Air Standard Efficiency," embodied in the 1927 Report of the Heat Engine Trials Committee of the Institution of Civil Engineers, compiled from figures supplied by the Author. Probably, however, the point of most interest is the close approach to the air-cycle standard efficiency under no-load conditions which the peculiar attributes of the compression-ignition engine have rendered attainable.

The Paper is accompanied by seventeen sheets of drawings, from some of which the Figures in the text have been prepared, and by the following Appendix.

[1] Proc. Inst. Auto. Eng., vol. 18, Part I (1923–4).

APPENDIX.

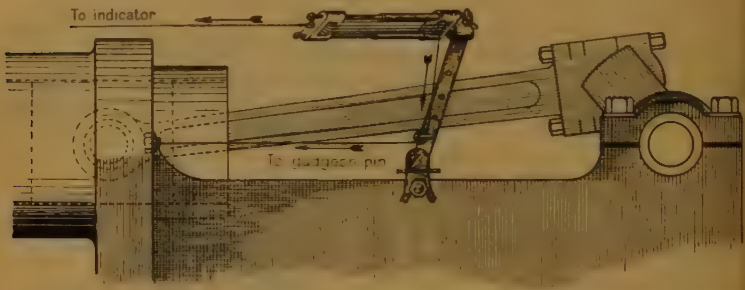
The indicator reducing-gear used by the Author for single-cylinder horizontal gas and oil engines in industrial service consists, as will be seen from *Fig. 14*, of a fixed element and a reciprocating crosshead, both housing five pulleys

Fig. 14.

grooved to receive indicating cord, and therefore giving ratios of reduction up to 10 : 1. The reciprocating crosshead is of aluminium, the pulleys are of steel on pins of ample diameter, and the guides on each side are brass tubes arranged in trombone fashion, each furnished with an internal spring around an inner steel rod. Screwed and riveted nuts at the extremities of the rods form safety stops in case of cord-breakage; this, however, with a little preliminary care to ensure that the cord leads directly to the pulley-groove without side friction, is a very infrequent experience. Two methods of application are indicated in *Figs. 15* and *16*, and it will be seen that, with one or two aluminium clamps, "Meccano"-like bars, and a few set-screws and thumb-nuts, the whole equipment can be set up securely and readily to suit all conditions. Even if

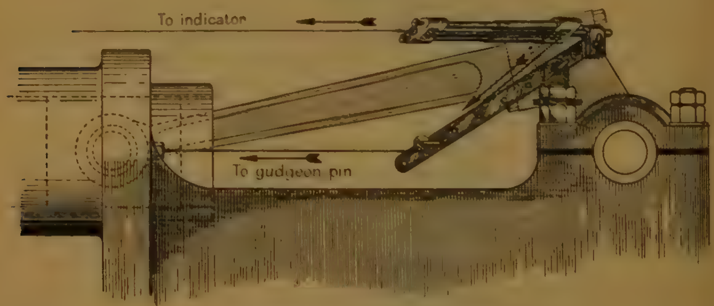
the indicator-plug is offset vertically or angularly from the cylinder-axis, or is placed horizontally at either side or even on the back cover, either a direct lead

Fig. 15.



from the reciprocating crosshead or the use of an intermediate swivelling pulley clamped to the water-outlet connexions can usually be arranged with little trouble.

Fig. 16.



The internal springs in the trombone-tubes relieve the indicator-drum spring of excessive stresses, and throughout many years the Author can recall only one or two replacements being necessary. Cord-stretch also gives no trouble, a fresh piece of cord, known commercially as "whip cord," soon becoming stretched to its maximum limit and afterwards needing no further adjustment. The method of fastening the cord to the fixed crosshead of the reducing mechanism is shown in *Fig. 15*; at the other end of the system of pulleys, the cord is made into a noose so that it can be slipped over the head of the piston-pin set-screw.

Discussion.

The AUTHOR, in introducing his Paper, remarked that the plotted points in *Fig. 1* (p. 169) referred to actual tests made under the usual conditions which obtained in the user's premises, and included the effect of any differences between the skill of different operators. It would be seen that they lay nearly on one line, and the line drawn through the upper points had been made the reference-line in subsequent Figures. The mixture-strengths recorded ranged from just below 20 to nearly 50 B.Th.U. per cubic foot. The lower limit of mixture-strength was almost the minimum at which regular explosions could be obtained in a gas engine. The range covered showed that the engines, when tested, were not all working at full load, but that some were working under the governing throttle. The Author.

Fig. 2 (p. 170) showed that magneto-ignition engines gave a higher thermal efficiency on the basis adopted than did tube-ignition engines. That was because with tube-ignition the timing was set, whereas with magneto-ignition it was possible to adjust the timing more or less to suit the conditions obtaining. The lowest mixture-strength was about 35, and the highest about 56 B.Th.U. per cubic foot, which showed that an engine governed by "hit-and-miss" always took a stronger mixture than a throttle-governed engine. Comparison of the test-points with the reference-line showed that the performance of engines with "hit-and-miss" governing was consistently better, owing probably to better scavenging on account of the "miss" strokes; the dotted line had been drawn to indicate, by comparison with the reference-line, the difference between a good throttle-governed engine and an equally good "hit-and-miss" engine.

Under industrial conditions it was not convenient to evaluate calorific values as was possible in the laboratory, and the thermal data given in the Paper had been computed from gas-meter readings.

The Author. The consistence of the results obtained under widely-varyin industrial conditions went far to refute the frequently-heard accusa tion that gas-meters were untrustworthy. The calorific value ha also to be taken as being constant; that assumption was safe, a the gas referees made daily tests to ensure that it did not vary fro the stated standard by more than a small percentage.

Fig. 5 (p. 180) indicated that the only important difference betwee a single-component gas, such as carbon monoxide, and a mixed ga such as coal gas, was the greater ignition-advance required by th former; that was due possibly to the absence of hydrogen, whic started the ignition in the coal gas.

Fig. 6 (p. 181), in addition to showing that no advance had bee made in the combustion-efficiency of the gas engine since 1908, gav an interesting comparison between the gas engine and the pressur charged compression-ignition engine. The latter was not limited t a minimum working mixture-strength of 20 B.Th.U. per cubic foo as for throttle-governed gas-engines, but was capable of running lig with high efficiency at no load, whilst with pressure-charging it wa possible to increase the amount of mixture so as to get an indicat mean pressure of as much as 120 lb. per square inch with a mixtur strength of 50 B.Th.U. per cubic foot.

The conclusion of the Paper was the tabulation of the quotient o the indicator mean pressure and the mixture-strength for a compres sion-ignition engine with mechanical injection; it was shown, pr bably for the first time, that such an engine under no load operat close to the air-cycle standard efficiency.

The President. The PRESIDENT congratulated the Author on his Paper, whic contained such interesting records of tests and conclusions therefro that it could be wished that Captain Sankey, Professor Burstall ar Sir Dugald Clerk could have been present, as they had been abo 30 years ago. It was Captain Sankey who had first called the rat of the mean pressure to the mixture-strength the "Tookey factor and it was interesting to see how it had become of definite val to the user for comparing engine-performances.

It was of special interest to The Institution to find that the "No on the Practical Application of the Air Standard Efficiency embodied in the 1927 Report of the Heat Engine Trials Committ of The Institution was supported by recent tests conducted by t Author, who found that at normal rated loads and average mixtur strengths the actual efficiency was 71 per cent., of the air-cyc efficiency, as compared with Sir Dugald Clerk's figure of 70 per cen It was also interesting to note that with compression-ignition engin when working on very weak mixtures under no-load condition 95 per cent. of the air-standard efficiency had been reached.

Sir JOHN THORNYCROFT remarked that the present Paper was particularly welcome, as few Papers dealing with the subject of internal-combustion engines had been discussed at The Institution since the War. The present-day motor vehicle and the aeroplane owed their development to the internal-combustion engine. While small power-plants on land had been diminishing in number with the introduction and extension of the supply of electrical power, marine engineers had been applying the internal-combustion engine to drive boats, and eventually ships. In the early days of the application of oil-engines to marine propulsion, Emile Capitaine, who had been one of the pioneers of the small high-speed oil engine on the Continent, had urged the adoption of gas engines for marine propulsion. A low-speed gas engine of 500 h.p. had been fitted in an experimental boat, and a number of engines of 150 and 200 h.p. in barges and other vessels. For the plant to be effective for sea-going ships, however, it was necessary to be able to use any type of coal that might be obtainable—bituminous coal, Welsh coal or anthracite—and the difficulties of developing a producer suitable for the conditions had been so great that no further progress had been made. It was of some interest to record, however, that an attempt had been made to use the gas engine in that way. Sir John Thornycroft.

The principal subject of the Paper was the ratio which the Author put forward, but that ratio did not give all the information desired, although a good deal of it. The Author's investigations had led him to certain conclusions, and he had brought forward evidence to corroborate them, but there were other factors to be taken into account in addition to those which the Author utilized in arriving at his ratio. It was known that some fuels permitted a greater proportion of the heat units which they contained to be converted into work than did others, and the degree of turbulence in the combustion-chamber of the engine had a very important effect. There were engineers present who had carried out extensive investigations of high-speed and low-speed diesel engines, and who would have much that was interesting and important to contribute to the discussion.

The Right Hon. Viscount FALMOUTH observed that it would be very useful to engineers to have such a large quantity of statistics and figures relating to the whole range of different classes of gas and oil engines brought together in one Paper. Lord Falmouth.

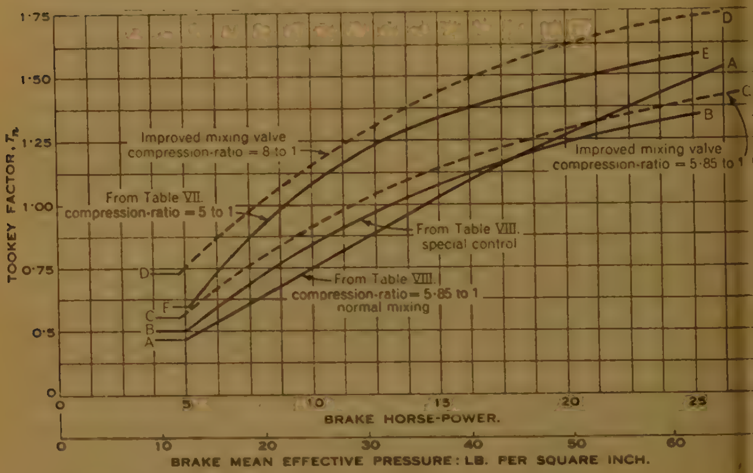
It would be interesting to know why the Author preferred the "Tookey factor" to the thermal efficiency as a basis of comparison between internal-combustion engines; the Author had had very long experience in testing engines, but those who were interested in designing engines nearly always employed the thermal efficiency.

Lord Falmouth.

Perhaps the Author would also say something more about his method of specifying "mixture-strength," because that term was often employed to denote the ratio of the fuel in the mixture, whether oil or gas, to the air. The Author, on the other hand, used it to denote the heat-intake per cubic foot of total cylinder volume. It was possible, of course, to vary considerably the amount of air admitted to a cylinder whilst injecting the same amount of fuel. In those circumstances, the mixture-strength would be varied under one definition and not under the other. He hoped that the Author would give his views on those points, because they were interesting and many others arose from them.

The figures given in Tables VII and VIII of the results of tests on

Fig. 17.



gas engines were very interesting. Lord Falmouth had had those figures plotted (*Fig. 17*), together with those of another engine with higher compression-ratio, for purposes of comparison. Curve gave the extrapolated figures of Table VIII (p. 177) for a small gas engine running under normal governing arrangements. Curve (from the same Table) was for the same gas engine, modified so as to have what was called in the Paper an automobile type of governor. It would be seen that line B showed a higher efficiency than A at low loads, but crossed line A at about three-quarter load. The maximum power of the engine was about 25 h.p. In further tests not mentioned in the Paper, the governing system had been again modified, and curve C was obtained, which was higher than B, but again crossed A at about three-quarter load. The compression-ratio

was then increased experimentally to 8 to 1, the results being as shown in curve D. Lord Falmouth.

It was stated in the Paper that there had been very little improvement in the gas engine, and *Fig. 6* (p. 181) showed that the compression-ignition engine had a considerable advantage. As would be realized, that was due to the fact that it had not been possible to raise the compression of the gas engine to anything like the same extent as that of the compression-ignition engine; his own company, however, had tried to raise the compression of the small engine to which he had referred, and with very successful results. It had been expected that there might be trouble with overheating of the exhaust-valves, but that had not been the case, and the improved efficiency had kept the exhaust-valve temperature down lower than in some of the other engines.

For comparison of the results which a medium-speed large engine would give, curve E had been plotted for the engine mentioned immediately beneath Table VI, p. 176. It would be seen how advantageous the high compression-ratio would be if it could be successfully adopted in gas engines.

An interesting point was brought out in *Fig. 5* (p. 180), which showed the importance of advancing the ignition in gas engines when working with weaker mixtures. That was not very easy to do, and many makers, though realizing that considerable improvement could be so obtained, fought shy of it because it entailed an additional complication, which might not be worth while in view of the fact that many of the engines were operated by unskilled men.

In *Fig. 11*, p. 187, the Author compared the performances of a six-cylinder compression-ignition engine with atmospheric and pressure charging. It would be of interest to know whether the valve-timing had been altered to suit the two different conditions, because generally there was an entirely different set of timing in the pressure-charged engine from that which prevailed in the engine working under ordinary suction.

Mr. A. E. L. Chorlton was a little disappointed that the Author had not dealt more fully with practical considerations, limitations, and factors which affected the results with different types of engines. He would, however, confine his remarks to certain other questions, the first of which was the indicator-gear. It was very important to use a good indicator-gear, and even more important that it should be properly put on the engine. The Author had not said whether he had met with cases where it had not been put on properly, but Mr. Chorlton had done so. Mr. Chorlton.

The Author had referred to the exhaust-pipe and to its effect on the running of the engine, and to the use of exhaust-gas calorimeters

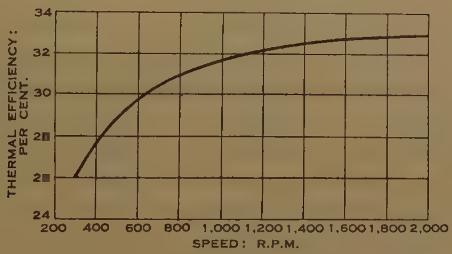
Mr. Chorlton. and other devices which he thought affected the passage of exhaust gas in the pipe. That was a very interesting subject, and mor should be done in the way of experiment. The effect of a prope exhaust-system was to be seen in the Petter two-stroke engine, wher the motion of the exhaust-gas was used to draw in the air for the nex working stroke. Many years before the War, he had tried to obtain simple relation by which it would be possible to determine the length of exhaust-pipes, but the usual difficulty was that a pipe, to give th correct period, had to be of impracticable length. As the Autho mentioned, Atkinson in the early days had used a long exhaust-pip to obtain a scavenging effect, but the idea had been dropped, probabl because of the length of pipe necessary. Mr. Chorlton had foun that the insertion of a square box in the pipe made it possible to us a much shorter pipe, as the first pulse passed into the box, an there was a short time-lag before the second pulse reached th box. The use of such an exhaust-system had caused a materia reduction in the pumping loss. Exhaust boilers had a serious effec if placed too close to the engine-cylinder, but they were very impor tant, particularly for large engines, and if the Author could give an information regarding their position it would be of great interes as they were nearly always placed close to the cylinder, whateve their form, so as to get the best heat-return possible. If the boile were arranged some distance down the pipe heat would be los owing to the distance, but if it were placed next to the engine ther would be a tendency for it to interfere with the pulsation of th exhaust-gases.

In making the very useful practical comparisons between engine given in the Paper, it was a pity that the Author had not indicate the nature of possible improvements arising out of them. Imme diately below Table I (p. 169), the Author said: " From this it will b observed that with increasing mixture-strength the thermal efficienc of engine performance in terms of indicator mean pressure decreased." That was true, but in almost every case there wa bound to be some explanation. In dealing with engines governe by the " hit-and-miss " method, the Author pointed out that th scavenging stroke, which brought in fresh air, was the explanatio of the higher mean pressure and the better results in compariso with throttle-governed engines, and Mr. Chorlton suggested tha in ordinary engine-design that should be borne in mind very muc more than it was. Immediately below Table III (p. 171), the Autho said: " Comparing the above difference-factors with those previous tabulated, it becomes evident that a higher combustion-efficiency attained with weaker mixtures . . ." That was so, and in th extreme case of an air-engine, in which there was no combustio

the efficiency became 100 per cent. of the air-standard efficiency; Mr. Chorlton. the Author had shown how nearly that figure had been attained with an oil engine with a very weak mixture.

The Author, on p. 179, made the very striking and explicit statement that "In gas-engine practice no advance in combustion-efficiency has been made since Professors Bertram Hopkinson and F. W. Burstall reported the results of their independently-conducted researches in 1908 at Cambridge and at Birmingham respectively." That was nearly 30 years ago, and Mr. Chorlton was very pleased to learn that Lord Falmouth's company had recently modified an engine and had obtained an improved efficiency from it. The difficulty in making a gas engine more efficient was that of using a higher compression-ratio, and he had hoped that the Author would have given some information in that respect. Great Britain was, after all, a coal-producing country, and everything possible should

Fig. 18.



therefore be done to use coal, and to use it economically. Lord Falmouth had said that in a particular engine the compression-ratio had been successfully increased from 5 to 1 to 8 to 1. It would have been interesting if Lord Falmouth had said something about the changes which had been made to allow the higher compression to be used, or why in earlier days nothing had been done to raise the compression. Lord Falmouth had mentioned the fear of overheating the exhaust-valve, but when working with a higher compression the heat-loss to the cylinder-walls and exhaust-valve was smaller, not greater. There did not appear to be any reason why the same economy should not be realized with a gas engine as was obtained with a diesel engine.

Fig. 18 related to the engine to which the Author referred (p. 184) when dealing with the effect of a rise in speed on the thermal efficiency. The improvement was of great interest, because it was of such great commercial value. A fast-running engine developed more power

Mr. Chorlton. than a similar engine running more slowly, and if it were possible t raise the economy at the same time it would be very useful; smal engines, and particularly those used in motor transport, had illus trated what could be done in raising the efficiency. In the Pape the statement was made that "... the high-speed engine, in con sequence of its lower mechanical efficiency due to greater losses i fluid and other resistances, falls short in comparison [with lower speed engines]; its range of practical mean pressures, however, i more extensive, due no doubt to the improved pumping efficiency or, in other words, the increase in volumetric efficiency due to th ramming effect of the kinetic energy imparted to the entering charg of air." Mr. Chorlton wondered whether the Author was quit correct in making that statement. With engines running at a spee of about 1,000 revolutions per minute, and with a stroke considerabl longer than that of the engine to which the Author referred, M Chorlton had obtained consumptions considerably lower, and quit equal to those on the higher curve of *Fig. 10* (p. 185). The difficult with a compression-ignition engine was that the conditions injection had to be taken into account; it was not possible simpl to weigh the fuel and to suppose that it had been injected effectivel and there might be quite a difference between one engine and anoth according to whether the injection was efficient or otherwise. I the case of the engine in question, it was not stated whether the was a turbulence-chamber or a simple chamber; the latter gave higher efficiency than the former, and that might explain th difference shown in *Fig. 10*.

Mr. Robinson. Mr. I. V. Robinson remarked that apparently what the Autho had done was not so much to explain why the efficiency of engin using a high "heat-density" was reduced as compared with tha of engines using lower "heat-densities," but rather to record th reduction, and to attempt to show the rate at which the efficien decreased. Mr. Robinson was a little surprised that the Auth had not devised formulas collating his columns of figures, an he had therefore made some attempt to do so, because when was said that, of two factors, one varied with the other at a certa rate it was very unsatisfactory to have to refer to a diagram and say that it showed, for example, how curve B varied with curve If it were possible to have an equation which connected the tw factors a comparison between them could be made much more easil He had therefore attempted to formulate some of the columns figures given in the Paper, and he would refer first to Table I (p. 171), in which the Author showed in the first column the quanti of heat per cubic foot—a short phrase for which was "heat-density —and in the next column what was termed P_m, which was t

dicator mean pressure in lb. per square inch. That gave the Mr. Robinson. quation

$$P_m = 2{\cdot}35Q_t - 0{\cdot}5 - 0{\cdot}01Q_t^2$$

he great advantage of that method was that if it were desired to nd the rate at which P_m varied with "heat-density," which was hat the Author was really giving in the column headed "difference-ctor," all that had to be done was to differentiate that equation. fter differentiating, it was found that the rate of variation of P_m ith Q_t was given by the expression $2{\cdot}35 - 0{\cdot}02Q_t$. That became ro when Q_t was equal to 117·5 B.Th.U. per cubic foot, and the aximum value of P_m which could be obtained, provided that the quation given above correctly represented the variation of P_m with $_t$, was 137·5 lb. per square inch.

He had adopted a similar method in connexion with Table VII). 176), which gave the equation

$$P_m = 3{\cdot}32Q_t - 22{\cdot}0 - 0{\cdot}017Q_t^2.$$

dopting the same procedure as before, the rate of variation of P_m ith Q_t was found to be $3{\cdot}32 - 0{\cdot}034Q_t$. The maximum value of $_m$ in that case was 140·1 lb. per square inch when Q_t was equal to 7·5 B.Th.U. per cubic foot. In Table VII the Author gave the alues of the brake mean effective pressures, and the differences etween them and the indicator mean pressures for different heat-ensities were 21·6, 20·5, 20·8, 17·6, and 23·0 lb. per square inch. ssuming a mean value of 21 lb. per square inch, the general expres-on for the brake mean effective pressure was

$$P_n = 3{\cdot}32Q_t - 43 - 0{\cdot}017Q_t^2.$$

he corresponding value for T_n was $3{\cdot}32 - \frac{43}{Q_t} - 0{\cdot}017Q_t$. If e latter expression were again differentiated, 1·719 would be und as the maximum value for T_n, and would occur when P_n was ·0 and Q_t was 50·3.

Still dealing with Table VII, and referring back to the figures ased on indicated pressure, by dividing the expression for P_m roughout by Q_t an expression for T_m was obtained, and by fferentiation the maximum value for T_m of 2·10 could be found. occurred for values of 36·0 for Q_t and 75·47 for P_m. It would observed that those figures giving a maximum value of T_m corre-onded almost exactly with the figures in Table VII for a heat-nsity of 36·3, which showed the maximum value for T_m.

The full line given in *Fig. 6* (p. 181) could be treated similarly, d gave the equation

$$P_m = 3{\cdot}15Q_t + 1{\cdot}56 - 0{\cdot}0156Q_t^2.$$

Mr. Robinson. Again differentiating and equating the differential to zero, the max mum value for P_m was found to be 161·56 lb. per square inch wit a heat-density of 100 B.Th.U. per cubic foot. If the equatio obtained from *Fig. 6* were divided through by Q_t, the expression f the Tookey factor T_m would be found to be $3{\cdot}15 + \frac{1{\cdot}56}{Q_t} - 0{\cdot}0156$(If that expression, in turn, were differentiated, the result wou show that T_m was always decreasing with an increase in the val of Q_t; that result was entirely contrary to what was found fro Table VII.

Table XV (p. 190) could also be treated in the same way, giving

$$P_m = 3{\cdot}00Q_t + 3{\cdot}3 - 0{\cdot}0131Q_t^2.$$

P_m had a maximum value of 175·06 lb. per square inch with a hea density of 114·5 B.Th.U. per cubic foot. Dividing the expressio through by Q_t to get the Tookey factor, it was found that, as f *Fig. 6*, T_m was always decreasing with increase of Q_t.

In Table XV the difference between the indicated and the bra mean pressure was generally about 18 lb. per square inch, a deducting that from the expression for P_m and dividing through Q_t, the general expression for T_n was found to be

$$3{\cdot}0 - \frac{14{\cdot}7}{Q_t} - 0{\cdot}0131Q_t.$$

That, by the usual treatment, gave a maximum value for T_n 1·563 when P_n was 53·75 and Q_t was 25·7.

With such equations it was possible to get quantitative values the rates of increase, and it should be possible to allocate so specific reason to the fact that, whereas with some test resu T_m was always decreasing, with others it was increasing up to so specific values of P_m. Mr. Robinson left it to the Author to say w there was that difference between the behaviours of different engin

The foregoing line of examination showed that there might some hope that the output of engines could be increased up to a me pressure of 175 lb. per square inch, and he wondered whether would be possible to achieve such mean pressures by the use special fuels—perhaps of the " dopes " of which so much was hea

With regard to the form of the equation, all those who had h any experience in equating figures knew that it was possible ove given range to adopt several forms of equation. Thus, as an alt native to the equation given earlier for Table XV, it would possible within the limits of that Table to express the figures qu accurately by the equation $P_m = 4{\cdot}757Q_t^{0{\cdot}8265}$. The drawback

ıe exponential equation was that a maximum point was not Mr. Robinson. ɒtained; the slope was ever decreasing but never became zero, so ıat there was no maximum, and in a case such as that which was eing considered he thought that it was desirable to have a curve hich had a definite maximum point.

It would be of interest to know whether the Author had ever ompared the rate at which heat was released in an oil-engine ylinder with, say, the rate at which heat was released in a large oiler. From figures which Mr. Robinson had it seemed to him ıat the rate of heat-release in an oil engine was at least equal to ıe rate of heat-release in the large central power-station boilers. would be of interest if the Author would look into that question ıd would give some definite information on the point.

Mr. Robinson called attention to the fact that the ratio in Table IV etween E_m and T_m was constant for any value of the volume-ratio r, ıd there would not appear to be any necessity for having reproıced the large number of figures appearing in Table IV (pp. 174 ıd 175). The ratio of E_m to T_m was given by the expression $\frac{-1,}{5 \cdot 4r}$ and was therefore independent of $(n-1)$. The efficiency self E_m did vary with $(n-1)$; those values might have been shown r any one value of r, and the variation of E_m with r for all values ɔuld also have been shown, together with the multiplier given by ıe above expression. That method of presentation would not have ɔpeared as formidable as Table IV.

In conclusion, he would point out that *Fig. 3* (p. 172) was true ıly for sea-level. If it were applied at Johannesburg, for instance, ere might be a repetition of the trouble which took place there me time ago!

Mr. V. G. Barford said that he had hoped that modern types of Mr. Barford. riable-speed engines, such as ordinary motor-vehicle engines, ɔuld have been dealt with in the Paper. He had often attempted use the Author's methods in the past, particularly in connexion th marine practice, where there were engines of large size which ı at more or less uniform speeds and which were sometimes indited, but the modern high-speed petrol engine was seldom indicated ing to the difficulty of doing so. It would have been most eresting had the Author explained how to deal with the problem ɔording to his method for a variable-speed engine, and especially he had given some advice regarding the determination of the lumetric efficiency. The Author's figures depended almost entirely knowing that efficiency, which had to be found before a start ıld be made.

There were one or two small criticisms which Mr. Barford wished

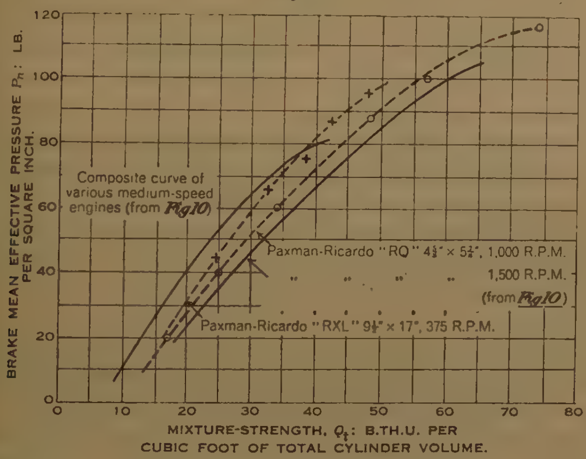
Mr. Barford. to make. With regard to *Fig. 12* (p. 188), he considered that it w
essential to draw a straight line from the common zero of the t
scales tangentially to the curves. That would at once indicate
point at which the "Tookey factor" was a maximum, which w
the most interesting point. *Fig. 12*, moreover, was one of the
cases where the common zero of the two scales was shown on
diagram. That was something which he considered should alw
be done, as graphs of the type in question were very decept
unless the common zero was shown. As an illustration, he wo
refer to *Fig. 4* (p. 178), where the zero of the mixture-strength
happened to come right at the edge of the page. It would be m
better if that were shown on the diagram, and then the metho
ruling tangents to the curves could be applied, and would ena
much useful information to be obtained and would save a good
of time. Generally speaking, the point of chief interest on the ch
was that which indicated the maximum efficiency, and if a tang
were ruled that point could be found immediately.

Mr. Paxman. Mr. E. P. Paxman agreed with Lord Falmouth in preferrin
simpler standard than the "Tookey factor," with all respect to
Author, because he thought that it was simpler to have the ther
efficiency expressed in absolute units, such as B.Th.U. per h.p.-h
or some equally definite standard which required no thought
explanation. It was then possible to correlate that or plot it w
any other factors desired, such as brake mean pressure at stand
speeds or at varying speeds, or indicator figures.

With regard to *Fig. 8* (p. 183), it was of interest to note that
maximum, or at any rate the more efficient, combustion was t
at higher speeds, and the figures at 1,500 revolutions per min
were substantially better than those at 700 to 800 revolutions
minute. *Fig. 9*, however, seemed to show an opposite result,
perhaps the Author could explain the apparent discrepancy. W
regard to *Fig. 10* and the Author's remarks on the higher-speed eng
Mr. Paxman thought that it was not only the question of speed wh
accounted for the lower efficiency of the engine; other factors w
the size of the cylinder and the extra heat-losses which were bo
to be expected when dealing, as in the case in question, with a sm
cylinder of 10 h.p. output at 1,000 revolutions per minute (wh
was about 1½ litre capacity), and comparing it with engines hav
outputs ranging from 65 to well over 200 h.p. per cylinder.
actual fact, as the Author said, if those figures were plotted on
indicated basis they came very much closer, but even then t
could be improved, as Mr. Chorlton had rightly said, by an impro
ment in the form of the combustion-chamber. Those figures had b
obtained on engines a year or two ago, and with the later form,

ark III Comet Ricardo engine, an improvement in consumption Mr. Paxman.
from $7\frac{1}{2}$ to 8 per cent. could be expected, and in *Fig. 10* that would
t the curve even for that small engine midway between the curve
rough the group of points and that for the high-speed engine. In
g. 19 Mr. Paxman had plotted some values for the larger type of
icardo engine running at higher speeds, but with a cylinder-capacity
mparable with those mentioned, and it would be seen that the
ints joined into the general run of curves from *Fig. 10* for engines
that size, which was interesting, and that at the top end of the
nge they extended very much farther. He disagreed with the
thor's statement that the additional output of the higher-speed
gine was obtained solely by reason of the ramming effect of
e entering air; that was not the case, because it was possible

Fig. 19.



produce the same mean effective pressure in larger engines of
atively low piston-speed; the high mean effective pressures could
obtained fairly easily. It was due to making use of the volume
air which was in the cylinder. In the case of the other engines to
ich the Author referred, if the figures given were their maxima
y were not using the air. On the other hand, it might well be
t they could use that air, but for fear of possible over-heating it
s not prudent to run them in that manner.
Mr. Paxman's firm had recently carried out exhaustive tests on a
v type of engine, and as a matter of interest, having regard to Mr.
binson's suggested maxima, it might be mentioned that the brake
an pressures of an unsupercharged engine with a stroke of $7\frac{3}{4}$ inches
e 131 lb. per square inch at 1,000 revolutions per minute and

Mr. Paxman. 126 lb. per square inch at 1,500 revolutions per minute. Tho figures corresponded to indicated mean pressures of well over 150 per square inch, when the frictional losses were taken into accoun

He would welcome the continuation of some of the curves show right down to zero indicated pressure, and he saw no reason w that could not have been done, because by motoring the engine a supplying part of the power it was clearly easy to get right do to literally no combustion in the cylinder at all. It would of interest in that case to see the effect on the efficiency by t standards which the Author had adopted.

Dr. Rowell. Dr. H. S. Rowell remarked that the Tookey factor was extremely useful number, and, if its dimensions were analysed, th was not surprising. The mixture-strength in B.Th.U. per cubic fo had the same dimensions as the indicator mean pressure in lb. p square inch, so that the "Tookey factor" was a non-dimension number which should be little affected by other variables. The eff of decreasing mixture-strength in increasing efficiency had been de with in a practical way. On p. 172, for example, an equation, wh involved the expansion-ratio, was given showing the relation the Tookey factor to efficiency. *Fig. 7* (p. 182) was a comprehens diagram which showed over a very great range the utility of Tookey factor. The surprising thing was that other variations that number were used very widely in engineering. Most engine who dealt with petrol engines spoke of the brake h.p. per litre 1,000 revolutions per minute, and on analysis that would be fou to be nothing more or less than a Tookey factor.

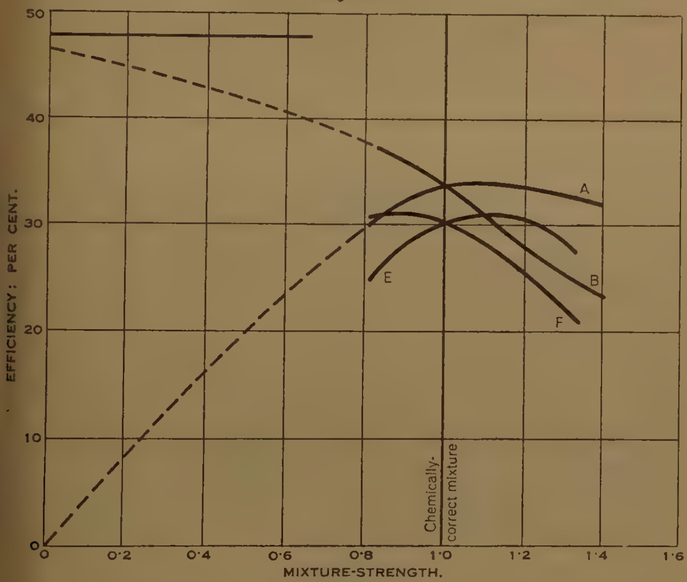
Professor Davies. Professor S. J. Davies observed that the Author had shown the Paper how good a practical criterion was the factor which b his name. Whilst that was very satisfactory as a basis of compari for the performance of existing engines, Professor Davies conside that something more was necessary in the case of tests made development purposes, with the object of improving existing desig

The Author referred on p. 190 to the work of Messrs. Tizard Pye, and mentioned that they gave a value of $n = 1{\cdot}258$ for corr mixtures and $n = 1{\cdot}296$ for 20 per cent. weak mixtures. He not, however, apparently think it necessary to point out the c ditions under which Messrs. Tizard and Pye had derived those figu The particular value of their work, to Professor Davies's mind, in the fact that their results represented a practical standar comparison which took into account all the properties of the fuel mixtures, such as variable specific heats, dissociation, etc., which did not take into account the imperfections of actual engi such as heat-losses to the walls, and unsatisfactory rates of c bustion. Their results were presented for a compression-ratio

to 1, with petrol–air mixtures, and had a fundamental basis rather than an empirical one. Professor Davies had therefore thought it well to carry out similar calculations to theirs, but applicable to Diesel-fuel-oil–air mixtures. Professor Davies.

Fig. 20 showed four curves: curve A was the original Tizard and Pye curve, while curve B was derived directly from that by dividing the values of A by the corresponding values of the mixture-strength, poorer and richer than 1·0 which corresponded to "chemically correct" proportions. Curve A showed the efficiency with which each lb. of air was utilized in the combustion when combined with various proportions of fuel; curve B showed the efficiency with which

Fig. 20.



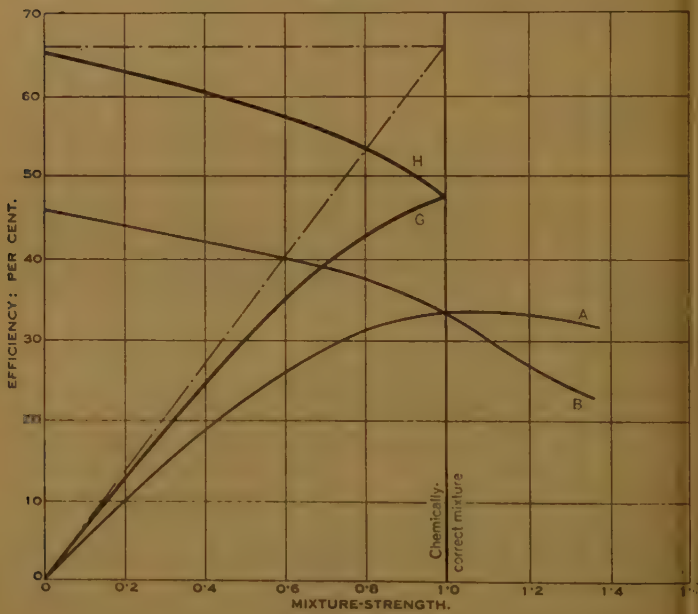
each lb. of fuel was utilized. Curve A intersected the origin; curve B intersected the vertical axis at a value slightly less than that corresponding to that of the air standard efficiency, the small difference being due to variable specific heats. Curves E and F in *Fig. 20* showed the results from Mr. Ricardo's variable-compression engine, and were given for comparison.

The curves G and H shown in *Fig. 21* had been calculated by Mr. C. Stevens, a research student at King's College, London. Those curves corresponded to curves A and B (reproduced for comparison), but they related to a compression-ratio of 15 to 1, and fuel-oil–air

Professor Davies.

mixtures, working on a constant-volume cycle. For oil engines it w not necessary to go beyond a chemically-correct mixture-strengt The differences between the heights of A and G, and B and H, respe tively, were merely due to the differences in compression-rati Under the conditions of the air-cycle standard, the efficiency on a fu basis had the constant value given by the broken horizontal lin while the efficiency on an air basis was the broken straight li passing through the origin. With actual working substances, taken in deriving curves G and H, the temperatures and pressu

Fig. 21.

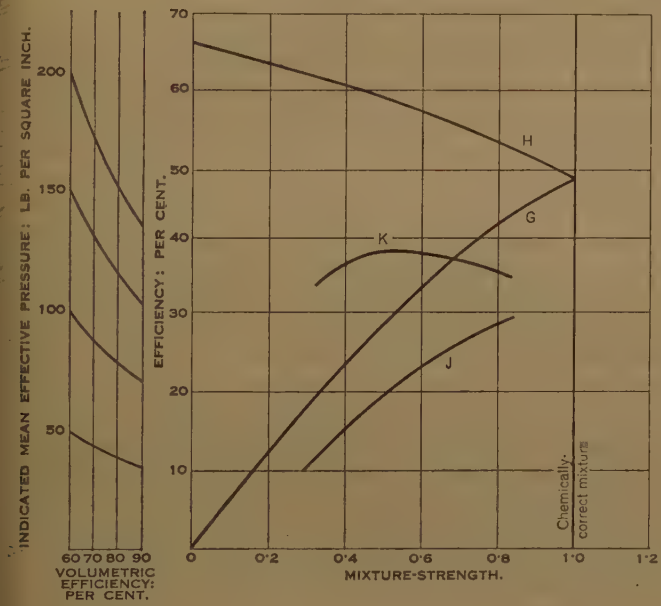


through which they passed during a cycle exerted a great influe on their specific heats and also on the amount of dissociation re-combination taking place. Since the ranges of temperature pressure were different for different mixture-strengths, the pract ideal efficiencies were modified accordingly. Curves G and showed the results of those deviations from air-cycle condition sloping away from the straight line and H having a pronou downward tendency with increasing mixture-strength. G and H course, intersected at the ordinate corresponding to correct mixt strength.

When curves derived from observations on actual engines w

ompared with the practical curves of reference, G and H, some Professor Davies.
ght was thrown on the conditions which determined output and fficiency. Other factors, as would be seen later, had to be taken nto account in judging the practical behaviour of engines, but clear deas concerning output and efficiency were obviously essential for ound design. A typical comparison was given in *Fig. 22*, where wo curves, J and K, derived from tests of a commercial high-speed il engine of similar compression-ratio, were shown against the eference-curves G and H. Curve J followed the form of curve G

Fig. 22.



airly well, and demonstrated that, as was realized in practice, the utput of mechanical energy per unit mass of air increased with ncreasing mixture-strength. Its general level was lower than that f G. The limiting output on curve J was taken at the point where he exhaust became visible, which was the usual practical limit. Curve J thus fell short of the reference-curve G in two respects: rstly, it lay lower at corresponding mixture-strengths, and secondly, t was limited as regards mixture-strength at the rich-mixture end of he curve. Dealing with the first point, it was clear that the higher hat curve J could be carried, at any particular mixture-strength,

Professor Davies.

the greater the output, and—since that was interrelated with efficiency on an air basis—the better the efficiency on a fuel ba Differences between curves G and J at any mixture-strength w due, on the one hand, to heat-losses to the walls, and, on the otl to deviations of the combustion from constant-volume conditio With regard to the second deficiency of curve J, it followed from upward tendency that the richer the mixture that could be burn without the exhaust becoming objectionable, the higher was maximum output to be obtained per lb. of air. In broad terr that limitation obviously depended on the efficacy of the proces for bringing the fuel into contact with the air supplied for its co bustion.

Professor Davies's remarks so far had been restricted to relative efficiency with which each lb. of air and fuel might utilized in the ideal cases (curves G and H) and in the act practical cases (curves J and K). It was, however, clear th other things being equal, the output of an engine of partic cylinder dimensions, as expressed by the indicated mean eff tive pressure on the piston, would also depend directly upon weight of air used for combustion in the cylinder in each cyc that was to say, on the volumetric efficiency. The indicated m effective pressure equalled a constant × (the efficiency on an basis) × (the volumetric efficiency). For a typical fuel-oil relationship was $P_m = 549\eta_a\eta_b$ lb. per square inch, where denoted the indicated mean effective pressure, and η_a and η_b deno the air-standard and volumetric efficiencies respectively, the ciencies being in fractional form. The values of the indicated m effective pressure corresponding to various values of volume efficiency were shown at the left of *Fig. 22*. The measurement volumetric efficiency presented little difficulty, either by dir means or by analysis of the exhaust gases; the latter method w for example, a regular routine observation on the buses of London Passenger Transport Board, in order to check the carburat and performance of their engines.

The Author did not mention volumetric efficiency in connex with Table XV (p. 190), and in considering existing engines it perhaps not necessary. Professor Davies, however, submitted t in development work it was essential to consider (*a*) the efficie with which each lb. of air was used, (*b*) the efficiency with wh each lb. of fuel was used, and (*c*) the volumetric or charging efficie of the engine under consideration. Only when the values of three of those efficiencies were known could the possible performa of the engine as regarded output and thermal efficiency be sat factorily analysed.

Mr. C. B. Dicksee said that the Tookey factor was extremely Mr. Dicksee. seful for those who had to deal in a practical way with engine evelopment. In the past, a method of comparison had been used hich involved taking the mean effective pressure plotted against he percentage of air used for the weight of fuel injected per unit olume of the cylinder. The Tookey factor, however, made it ossible to compare directly values obtained at different loads. he Author's method gave the mean slope of the curve up to the oint that was being considered. Mr. Dicksee thought that a good eal more attention should be paid to the brake mean effective ressure than to the indicated mean effective pressure. The latter as very useful to enable nice low consumption-figures to be quoted, ut it did not mean much to the actual user, and on high-speed ngines, with which Mr. Dicksee was associated, it was very difficult o obtain accurately the indicated mean effective pressure. The sual method employed was to motor the engine, hot, at the speed nder consideration and to add the mean pressure corresponding o the motoring h.p. to the value of the brake mean effective presure; that was probably at least as accurate as measuring the verage indicator-diagram. Under those conditions on small highpeed engines it was possible to obtain figures which compared very avourably with those of the large slow-speed engines.

He had taken some figures from the latest type of Ricardo ombustion-chamber recently tried out on a six-cylinder 8·8-litre ngine. The maximum indicated mean effective pressure obtained as from 140 to 145 lb. per square inch over the speed-range, and he interesting point was that over a speed-range of from 1,000 to ,000 revolutions per minute there was practically no difference in the ean effective pressure on the indicated basis, showing that such ifferences as were obtained on the brake basis were entirely due o mechanical considerations. With the engine adjusted for 100 h.p. t 1,500 revolutions per minute, the figures were 51·6 B.Th.U. per ubic foot at 1,000 revolutions per minute, the Tookey factor being ·32, and 55·5 B.Th.U. per cubic foot at 1,500 revolutions per minute owing to the rising metering-characteristic of the pump) with a ookey factor of 2·28. At 2,000 revolutions per minute the heatalue was 56 B.Th.U. per cubic foot and the Tookey factor was ·31. His firm had repeatedly found that when the results were lotted over speed-ranges there was very often a slight tendency owards improvement at the higher speeds as compared with the ower speeds on the indicated basis, showing that where there was dequate swirl there was no loss of thermodynamic efficiency with peed, because the combustion was able to keep pace with the iston-speed.

Mr. Dicksee. The suggestion had been made in the discussion that the te should be run down to no load. They had actually run down about one-third of the no-load indicated power, using an elect dynamometer feeding back to the line. At about one-half of t no-load indicated power the efficiency tended to fall away, but do to that point it kept well up and followed the trend obtained do to no load. Volumetric efficiency had also been mentioned. W an ordinary hydrocarbon fuel in which the carbon/hydrogen ra was known, a carefully-taken exhaust-gas analysis would make possible to work out the volumetric efficiency with a high degree accuracy, and that was a simple and effective method which did r require a large amount of apparatus.

Mr. Beaumont. Mr. E. G. BEAUMONT remarked that in the last paragraph of t Paper the Author referred to the close approach to the air-cy standard efficiency as being probably the point of most intere from what was stated in the Paper, however, and from the rema of many preceding speakers, a point of outstanding interest was high maintained thermal efficiency of the small engine in relat to that of the big engine. It would be noticed, for instance, t the small high-speed engine referred to in Table XI (p. 186) show a Tookey factor of 1·775, while the highest Tookey factor of industrial-type engine was 2·07. In Table XIII (p. 188), referr to the two big marine engines, the figures were respectively 2·04 the *Polyphemus* and 1·94 for the *Maron*. It would seem, therefo utilizing the figures given in those Tables, and the curves in *Fig.* and *Fig. 12*, for determining the factors, that the examples inclu in the Paper showed that quite small engines had a thermal efficie as high as, and in some cases higher than, that of engines which w thirty or forty times as large.

The Paper was devoted to a large extent to a review of gas-eng thermal performance, and what the Author termed the mod high-speed compression-ignition development was necessarily trea somewhat cursorily, but Mr. Dicksee had called attention to the f that if modern examples of the small high-speed road-transp compression-ignition engines were taken into account Tookey fact of well over 2 could be found. He had witnessed a test of an eng running at 1,500 revolutions per minute, which showed a f consumption of 0·375 lb. per brake h.p.-hour, the higher calor value of the fuel being 19,400 B.Th.U. per lb. The engine develo 78 brake h.p. and had an equivalent heat value of 46·5 B.Th.U. cubic foot, with a brake mean effective pressure of 98 lb. per cu foot and a Tookey factor of 2·1. That was not an isolated exam but was one of many similar cases.

The Paper formed a record which would be of value in years

ome in enabling a comparison to be made with later practice, and or that reason Mr. Beaumont suggested that the particulars given f some of the engines in the Paper should be amplified, for example, n respect of their compression-ratio, bore and stroke, and injection-ystem, so that their leading characteristics might be known. If hat were done it would enhance the value of the Paper. Mr. Beaumont.

*** Commander W. G. Cowland observed that the Author's nethod of comparing the performances of internal-combustion ngines was of especial interest to the Admiralty Engineering aboratory, where a somewhat similar method was used for com-aring the performances of compression-ignition engines. In the nethod employed there the basic factor for comparison, which as called the "combustion-factor," was proportional to the nergy supplied to the engine per unit of the volume swept by the iston in the firing stroke. The combustion-factor was derived as ollows:— Commander Cowland.

Let E denote the energy supplied per cycle per unit of piston-swept volume in the firing stroke.
,, F ,, ,, fuel-consumption in lb. per hour.
,, J ,, ,, Joule's Equivalent in foot-lb. per B.Th.U.
,, C ,, ,, calorific value of the fuel, in B.Th.U. per lb.
,, V_s ,, ,, piston-swept volume in cubic feet.
,, N ,, ,, number of firing strokes per minute.

hen the energy supplied per minute $= \frac{F}{60} \times C \times J$, and, since the wept volume multiplied by the firing strokes per minute $= V_s \times N$,

hen
$$E = \frac{F}{V_s \times N} \times \frac{C \times J}{60} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

ut, from the horse-power formula,

$$\frac{144\, V_s \times N}{33{,}000} = \frac{\text{brake h.p.}}{P_n} = \frac{\text{indicator h.p.}}{P_m},$$

here P_n denoted the brake mean effective pressure, in lb. per square inch,
nd P_m ,, ,, indicator mean pressure, in lb. per square inch.
hen, substituting in (1),

$$E = \frac{144 \times C \times J}{60 \times 33{,}000} \times P_n \times F_n, \quad . \quad . \quad . \quad . \quad . \quad (2)$$

*** This contribution was submitted in writing.—Acting Sec. nst. C.E.

Commander Cowland.

where F_n denoted the fuel-consumption per brake h.p.-hour in lb.

or
$$E = \frac{144 \times C \times J}{60 \times 33{,}000} \times P_m \times F_m, \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where F_m denoted the fuel-consumption per indicated h.p.-hour in

Of those two expressions, the former was to be preferred, since and the brake h.p. could be determined for any engine with a hi degree of accuracy, whereas the measurement of P_m was subject greater error and was limited to low-speed engines.

If the product $P_n \times F_n$ were called the "combustion-factor,"

$$\text{then } E = 0{\cdot}0566 \times C \times \phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

For a given fuel ϕ was directly proportional to E. Since the fu used in compression-ignition engines had approximately the sa calorific value, the value of ϕ could be used as a basis for graphi comparison of engine-performances.

The simple product of P_n and F_n was thus readily determin from measurements that could be made with a high degree of accura and that were invariably made in the normal course of testing engine. If comparisons of performances were to be made for engi using fuels of widely-different calorific values, for example a co parison between a gas engine and a compression-ignition engine would be necessary to use values of E calculated by means of eq tion (4). In calculating E for the gas engine, the consumption wo be expressed in cubic feet per brake h.p.-hour, and the calorific va in B.Th.U. per cubic foot. It was suggested that in such cases combustion-factor, based as it was on piston-swept volume, v more readily determined, and was a truer basis of comparison, th the Author's factor Q_t, which favoured the engine with the lo compression-ratio.

A diagram in which values of P_n were plotted against the corr ponding values of ϕ, whilst being a graphical representation of engine-performance, also contained the information for the rea calculation of :—

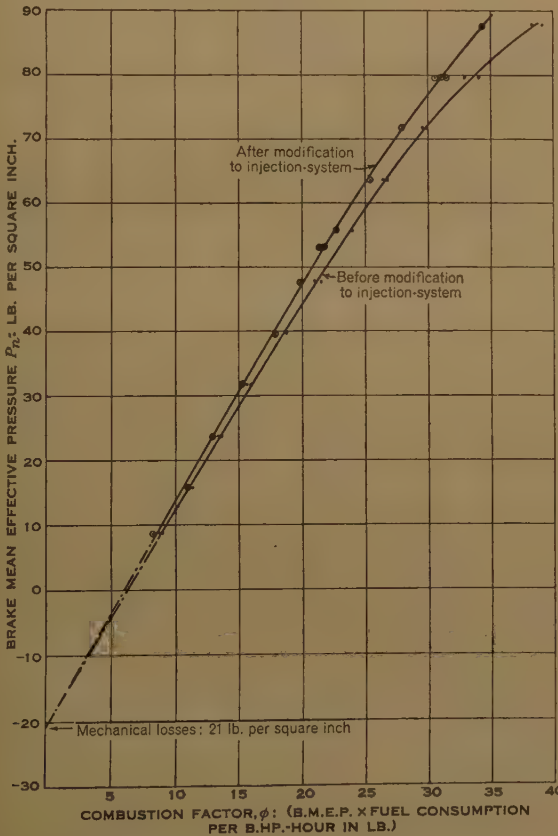
(a) the fuel-consumption per brake h.p.-hour $= \dfrac{\phi}{P_n}$

(b) the thermal efficiency (brake) $= \dfrac{P_n}{\phi} \times \dfrac{2{,}545}{C}$

For low-speed engines, where P_m could be determined with reas able accuracy, the graph of P_m against ϕ showed the combustion-p formance of the engine. The fuel-consumption per indicated h hour and the thermal efficiency could be calculated by the appropr

ıbstitutions in the relations given above. For high-speed engines ıe graph of P_n against ϕ for a range of powers at constant speed ıight be used to estimate the mechanical losses and the correspond- ıg values of P_m at that speed.[1] An example of the application for a nall four-cylinder "direct-injection" engine was given in *Fig. 23.* hat diagram was also of particular interest in showing the improve- Commander Cowland.

Fig. 23.



ıent of combustion-performance obtained by adjustment to the ıel-injection system while the mechanical losses remained unaltered.

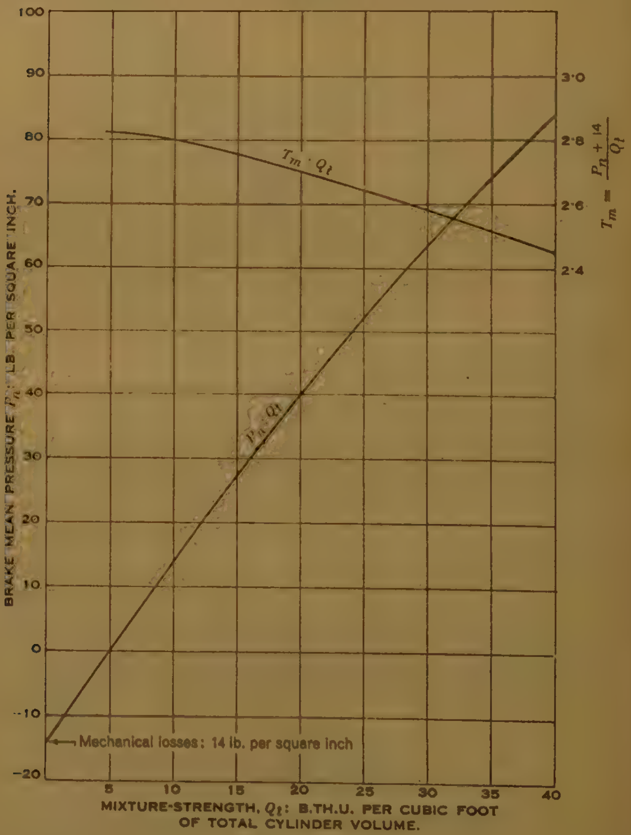
Use of the combustion-factor also simplified the calculation of the olumetric efficiency of the engine. The percentage of excess air ʼas first determined from an exhaust-gas analysis. The volumetric

[1] W. G. Cowland and P. Henderson, "A 'Combustion Factor' Diagram for .I. Engines." *The Engineer*, vol. clxiii (1937), p. 183.

Commander Cowland.

efficiency was then given by $\eta_v = \left\{1 + \left(\frac{\text{percentage of excess air}}{100}\right.\right.$ $\times$ 0·0138 $\times \phi$. The constant given was for fuel requiring 14·5 l of air for complete combustion of 1 lb. of fuel, and η_v denoted t ratio $\left(\frac{\text{air induced}}{\text{piston-swept volume}}\right)$ per suction stroke, in terms of air 60° F. and 14·7 lb. per square inch absolute.

Fig. 24.



In conclusion, he would draw the Author's attention to *Fig.* (p. 189). In that figure the form of the T_m-curve was incorrect a tended to an impossible value of thermal efficiency when Q_t was ma zero. The values of P_n and Q_t given in Table XV (p. 190) had be plotted in *Fig. 24*. Extrapolation of the line indicated mechani

sses equivalent to 14 lb. per square inch, as compared with the 18 lb. er square inch stated on p. 189. Using the lower value for the echanical losses to compute new values for P_m and T_m, the resultant T_m-curve, also plotted in *Fig. 24*, was seen to be normal in form, but ie corresponding thermal efficiencies were, of course, much lower han those quoted in Table XV. Commander Cowland.

The AUTHOR, in reply, observed that Sir John Thornycroft had ferred to other factors that influenced the performance of internal-ombustion engines, besides those that were taken into account hen comparing the mean pressure with the mixture-strength of the iel admitted at each cycle as shown by the Tookey factor, and had stanced variations in fuel-characteristics and in the degree of irbulence, which in some engines were very important. It should pointed out, however, that fuel-characteristics and turbulence ere physical and mechanical differences respectively, whilst the tio between the work output in terms of mean pressure and e heat input in B.Th.U. was a true and basic measure of com-istion-efficiency as actually achieved by any engine of any type of nstruction with any fuel. Lord Falmouth and Mr. E. P. Paxman id intimated that the comparison between engine-performances on e basis of thermal efficiency was commonly expressed as the rcentage of the heat in the fuel converted into work in terms of dicator h.p. or preferably brake h.p., and that that method gave formation desired by designers and experimenters. That fact as, of course, undeniable, but in the Author's experience it was quisite when studying differences in engine-performances, and pecially in the development of new types or improvement of old ies, to realize the actual number of heat units taking part in com-istion at each impulse, and not merely the standard of performance hich the "thermal efficiency" as usually stated connoted. In int of fact, the Tookey factor was an index to thermal efficiency, shown by the formula at the foot of p. 172. When exhaust-gas ermometer readings and exhaust-gas analysis in terms of CO_2 re plotted on the mixture-strength basis adopted by the ithor, the performance of an engine could be studied analytically a manner impossible when thermal efficiency was the only measuring-stick." The Author.

The reason why the Author preferred the mixture-strength to be pressed in terms of fuel only was that the basis of Q_t was easily lculated. For any engine of which the clearance-ratio was known, could be closely estimated, it was a simple matter to compute the tal cylinder-volume for a single- or multi-cylinder engine. Know-g the engine-speed, the number of impulses per minute would per-t the total cylinder-volume per minute to be ascertained. The

The Author. rate of fuel-consumption per minute multiplied by its calorific val divided by the total cylinder-volume per minute gave the value of (For engines running at a uniform speed at all loads a "constant could be calculated at the beginning of each series of tests whic when multiplied by the observed rates of fuel-consumption, would once give the values of Q_t.

The amount of air present in any internal-combustion engi cylinder was not readily determinable, and, after all, it was t number of heat units consumed that finally determined the perforı ance of the engine. With due deference to those who employed t term "unity mixture-strength," and expressed variations as many per cent. weak or strong as the case might be, those expressic were of little value to the engineer whose task was to get throu a series of engine-tests with expedition and to report results unc commercial conditions. Such a man wished to compare one engi with another, and if, for example, one gave a smoky exhaust wh another ran with clean exhaust he wanted to be able to detect t cause of the trouble. Obviously it was important to know wheth the strength of mixture in B.Th.U. was the same in each case fo given power-output. The mixture-strength expressed in the fo Q_t would at once give him a correct basis for such a determinati and he could then check the injection, timing, turbulence, volumet efficiency, and so on with greater confidence. On the basis employ by the Author it was immaterial, as the Paper showed, whether air was throttled, induced at atmospheric pressure, or forced in pressure. In the first case the rate of fuel efficiently consumed wo be strictly limited, and in the third the normal rate would be ceeded, but the relation of the heat input Q_t to the output expres as brake mean effective pressure or indicator mean pressure wo be on the same simple basis in all three cases.

The improvement in efficiency brought about by higher co pression-ratios, as mentioned by Lord Falmouth, was well known had been indicated by the Author in 1914 in the discussion o Paper.[1]

The answer to Lord Falmouth's final question (p. 197) was t the points plotted in *Fig. 11* were all from the same engine with same valve-timing. The latter had been altered from the us timing for normal atmospheric charging in the direction of a lo period of overlap of exhaust and inlet openings.

Mr. Chorlton had expressed disappointment that the Paper been limited in scope. The discussion showed that already eno subjects had been included to provide material for a welcome amo

[1] Footnote (3), p. 167.

The Author.

f criticism, and, as the chief object was to compare the performances f commercial engines and to indicate similarities, it would have ouded the issue to have endeavoured to deal with the practical onsiderations, limitations and factors which brought about dis-milarities. The Author has touched upon exhaust-pipe resistances relation to combustion-efficiency only, and had not attempted to eal with the many questions of heat-recovery to which Mr. Chorlton ad directed attention. It might, however, be mentioned that robably the most modern installation for the recovery of heat from e exhaust-gases was that referred to in a recent Paper by Mr. . M. Watson.[1]

Mr. Chorlton had expressed a doubt whether the Author was correct stating that increase of air volumetric efficiency was sometimes due the "ramming" effect occasioned by the kinetic energy of entering arges of air. The Author unhesitatingly repeated his opinion, and ould instance improvements in the performance of two-stroke-ycle engines of the crankcase-compression type when air-trunks ad been fitted to the crankcase valve-covers. Similarly, certain igh-speed diesel engines were notorious for "dirty" exhaust, and ose were of a design which provided no passage through which e entering air could acquire velocity. It was now not at all ncommon to find engines made with inlet-valves larger than exhaust-alves, so that the exhaust-gases left at high velocity and thus gave greater induction effect to the entering column of air, so as to ncourage the ramming effect.

The contribution of Mr. I. V. Robinson was very interesting. he Author had worded his Paper to avoid mathematics as far as ossible so that it could be understood and perhaps made use of by actical men who had little time for anything but their own im-ediate duties. The upper limits of P_m and Q_t computed by Mr. obinson from the curves given were certainly of interest, and it was fact that a value of P_m of 140 to 160 lb. per square inch was pparently the maximum obtainable by normally-charged engines. resent practice seemed to set a limit to P_m of about 100 lb. per uare inch for both gas and oil engines when atmospherically charged —in the words of the British Standard Specification—they were xpected to work "without undue heating or other mechanical ouble." Mr. Robinson was quite correct in commenting that *Fig. 3* . 172) referred only to sea-level conditions, but the actual com-ession-pressure attained at high altitudes could be computed by arying the numeral 15 given in the formula (which represented the

[1] "West Middlesex Main Drainage." Journal Inst. C.E., vol. 5, (1936–37) 463. (April 1937.)

The Author. atmospheric pressure with the barometer at 30 inches of mercu to accord with the height of barometer at the high altitude. I reference to a case at Johannesburg was surely inappropriate. was not the high altitude that had caused trouble but the del quencies of the gas-producing apparatus.

With regard to the differences to which Mr. Robinson had cal attention in respect of the behaviour of different engines, the reas was to be found in the fact that, whereas the compression-igniti engine was designed to create a compression-temperature above t ignition-point of the fuel, gas-engine charges could only be fired electric or other means and the resulting rate of flame-propagat was then not constant at all degrees of mixture-strength becaus the influence of the skin-temperature of the cylinder-walls, wh might be high at or immediately after full loads and low at light loa

Mr. Barford would realize from what had already been sta in reply that there was no need for him to worry overmuch ab volumetric efficiency. The combustion-efficiency mattered m and, as Mr. Dicksee had pointed out, a simple test with an Or type apparatus to determine exhaust-gas composition would giv direct indication of the sufficiency or otherwise of oxygen in air charge. With regard to Mr. Barford's suggestion that common zeros for both scales of the Figures should have been sho the original diagrams had been drawn in that manner, but for re duction in the Journal it had been thought better not to have much blank space.

If Mr. Paxman preferred to employ B.Th.U. per brake h.p.-h as a standard of comparison, he at once complicated his figures quantities which involved cylinder-dimensions and speed—mat which surely involved more thought and explanation than fundamental bases of B.Th.U. per unit of volume and mean pres per unit of piston-area. Habit was usually inimical to change, perhaps later on Mr. Paxman would find his habit old-fashioned somewhat restrictive. Regarding the question of heat-losses seemed to the Author altogether wrong to attribute low combust efficiencies to their effect. Heat was not released from fuel u it was burnt, and therefore the combustion-efficiency depended m upon pre-treatment before ignition than upon losses after igni to the water-jacket, to the exhaust, and by radiation. If Mr. man would plot performances on the basis of Q_t, and then, know the thermal efficiency, would calculate upon the accepted b how many heat units were actually converted into work, he w find that towards the maximum output of any engine the numb heat units converted remained almost constant, the number of units passing to water also remaining almost constant but

umber escaping to exhaust increasing vastly. That was a lesson The Author.
hat the use of B.Th.U. per h.p.-hour entirely cloaked. Mr. Paxman
o doubt realized that piston-speed in itself gave no information
garding the ramming effect.

Dr. Rowell's remarks were most welcome, as were those of Mr.
icksee, and the experience of both gentlemen was such that their
pinions were particularly valuable. It was because the Author
alized that commercial considerations favoured comparison on a
asis of brake mean effective pressure that he had brought into his
ables the ratio P_n/Q_t. Mr. Beaumont's comments were also much
ppreciated.

Professor Davies had been to some trouble to co-ordinate the work
Messrs. Tizard and Pye on mixtures of petrol and air with his own
ork on mixtures of diesel-oil and air. The Author was of the
pinion that the evaluation of mixture-strength in terms of the
emically-correct mixture, which was taken as unity, was more
itable for academic than for commercial purposes, since it entailed
computation from an accurate fuel-analysis and could not readily
employed on the test-bed or in the works. The Author had
ready propounded his views with regard to heat-losses to cylinder-
alls, but it might perhaps be further stated that many experiments
many engineers in the development departments of many manu-
cturers had failed to find that efficiency was greatly, if at all,
fected by varying cylinder-wall temperatures. Combustion-
iciency depended largely upon pre-treatment of the charge before
nition and—as Professor Davies had stated—upon the efficacy of
e processes of bringing fuel into contact with air before and during
mbustion. The reason why the Author had not specially
entioned volumetric efficiency had already been explained.

Commander Cowland's valuable work at the Admiralty Engineer-
g Laboratory was known to the Author from a personal visit and
om discussions at various times. It would perhaps be interesting
record that the Author's formula for computing the brake mean
ective pressure was WK/N,

in which W denoted the output per cylinder in brake h.p.,
K ,, a constant $= 229/V_s$.
V_s ,, the piston-displacement in cubic feet, and
N ,, the impulses per minute;

Q_n denoted the B.Th.U. per brake h.p. per minute,

$$229 \times \frac{r}{r-1} \div Q_n = T_n,$$

d

$$Q_t = P_n/T_n.$$

The Author. Those formulas were applicable to all internal-combustion engin whether using gaseous or liquid fuel. The Author preferred express the mixture-strength in terms of B.Th.U. per cubic foot total rather than of swept cylinder-volume, because the larger t clearance-space the more heat units had to be present to bring t mixture-strength before combustion to a given heat-density and v versa. The values of P_m/Q_t then permitted comparison of comb tion-efficiencies irrespective of the change of efficiency direc attributable to change of compression-ratio. The additional co bustion-efficiency attained beyond that due to a change in the va $r/(r-1)$ could not be appreciated unless the value of Q_t were tak as a basis of comparison. As to the form of the curve of T_m in *F 13* (p. 189), the upper limit for a thermal efficiency of 100 per ce —with zero mixture-strength in zero clearance volume—was, course, 5·4 (as was shown by the formula at the bottom of p. 17

The extrapolation acceptable to Commander Cowland in *Fig.* (p. 216) assumed a mean combustion-efficiency which did not incre at the lower output. One of the Author's objects in writing Paper had been to point out that combustion-efficiency at li loads increased at a rate which had hitherto been unsuspected. was the compression-ignition engine's immunity from the exter influences that otherwise would prevent prompt ignition of w charges that had, at last, enabled engineers to realize that fa The column headed "Difference-factor" in Table XIV (p. 1 was surely conclusive on that point.

*** The Correspondence on the foregoing Paper will be publis in the Institution Journal for October, 1938.—ACTING SEC. INST.

ORDINARY MEETING.

16 November, 1937.

SYDNEY BRYAN DONKIN, President,
in the Chair.

The following Paper was submitted for discussion, and, on the motion of the President, the thanks of The Institution were accorded to the Author.

Paper No. 5146.

"Dover Train-Ferry Dock."†

By George Ellson, O.B.E., M. Inst. C.E.

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History.

The first record of a scheme for communication between Dover and the Continent by means of a Channel ferry is of that proposed by Mr. (afterwards Sir) John Fowler, Past-President Inst. C.E., who gave the project considerable attention from the year 1864 onwards. Fowler selected Dover as the best starting-point on the English side. At about that time proposals had been put forward for both a Channel tunnel and a Channel bridge. The latter proposal he discarded as too ridiculous to discuss; as to the former, he regarded his proposal

† Correspondence on this Paper can be accepted until the 15th March, 1938.
—Acting Sec. Inst. C.E.

for a ferry as comparable with a tunnel in the sense that it was a continuous communication, the essence of it being that carriages, goods-trucks and mails should be carried across without breaking bulk. He had in view boats of about 450 feet long, 6,000 tons burden and 10,000 horse-power, capable of carrying a train of sixteen carriages, the weight of which he estimated at a little over 100 tons.

He proposed that a new harbour of an area of 95 acres should be obtained so as to secure perfectly still water for the use of the ferry-boats. The water-station was to be fitted with hydraulic lifts, wharves, and the necessary apparatus for the passage of the trains to the steamer. The hydraulic lift was to be half as long as the vessel, and trains of the London, Chatham & Dover and the South-Eastern Railway Companies were to be put on the lift as they arrived and run on board the boat side by side. Sir William (later Lord) Armstrong, Past-President Inst. C.E., had been consulted about the machinery, and undertook to provide lifts which would complete the operation in 1 minute. Mr. Fowler, more cautiously, thought that 5 minutes would not be an unreasonable delay; he estimated the cost of the works at £890,000.[1]

The French Government gave favourable assurances regarding their end of the Ferry, and a Bill to authorize the works came before Parliament in 1872. It passed the House of Commons Committee, but owing to lack of support from the South-Eastern and the London, Chatham & Dover Railway Companies it was thrown out by the House of Lords Committee.

In more recent years powers have been obtained on three occasions for the construction of docks at Dover at or near the site of the train-ferry dock, the last proposal being authorized in 1920, the Engineers being Messrs. Baker and Hurtzig and Mr. A. T. Walmisley. These proposals were, however, abandoned.

During the War, and for a short time subsequently, train-ferries which rendered great service were operated between the port of Richborough, on the Dover and Deal line, and Calais, but the necessary depth of water required for the vessels to reach their berth at Richborough only existed at high water, and constant dredging of the channel of the river Stour at heavy cost was required to maintain it.

When the Channel Tunnel Commissioners' report was issued in 1930 and the subsequent Government decision against the carrying out of the scheme in the near future was announced, the Southern Railway Company decided to proceed with a train-ferry scheme connecting Dover with a port on the other side of the Channel.

[1] T. Mackay, "Life of Sir John Fowler," p. 206.

Design of Works.

The considerations which led to the selection of Dover as the most suitable site for the English terminal were as follows :—

(1) Its proximity to France.
(2) Its convenient rail access to and from London.
(3) The availability of the necessary depth of water at all states of the tide.

The most suitable site available at Dover for berthing the ferries was one immediately adjacent to Dover Marine station, where rail access was directly available. Besides adding to the convenience of working and supervision, the close proximity of this site to the existing Marine station also has the great advantage of allowing convenient interchange between that station and the ferry of rail-passengers other than those proceeding to the Continent by through sleeping-cars.

The ferry-vessels for the cross-channel services were designed with a length of 359 feet, a beam of 63 feet 9 inches, and a mean laden draught of 12 feet 6 inches. The train-deck carries four railway-tracks capable of holding a total of twelve coaches or forty wagons. The after part of the train-deck is also available for holding large motor vehicles which cannot conveniently travel in the garage on the upper deck. The vessels have a gross tonnage of 2,839 tons, with 4,900 indicated horse-power.

The ordinary method of constructing a ferry terminal would not have been possible at Dover, as there is an extreme range of 25 feet between the highest and lowest water-level at spring tides, and the passage of such vehicular traffic as long bogie-coaches between the ferries and the shore would have necessitated at lowest tides an inclined approach about 500 feet long. The raising and lowering of such a structure to the required gradients to suit any tidal conditions, coupled with the extreme difficulty which would have been found in mooring a vessel in the open water of the harbour at the end of such an approach and keeping it there during transhipment of traffic in any but calm weather, would have rendered the working of the services impracticable. As it is necessary to work a regular train-schedule with probable future extensions of the services, it was decided that the scheme should consist of an enclosed and water-tight dock in which to berth the ferry-vessels, where the water-level could be raised or lowered by pumps to the required berthing level, and the dock-gates could be opened and closed in practically all weathers.

The geological formation of the sea-bed at the site selected consists of the lower grey chalk. Many engineering works which have been

carried out in the vicinity have consistently revealed the chalk to be of a solid and homogeneous character, and additional mention may be made of the following experimental works which have been executed for the purpose of ascertaining the nature of the chalk from the point of view of its being impervious to water :—

(1) A heading driven in 1880 from a site at the foot of Abbotscliff above the level of the sea, which at the present time is in a wonderful state of preservation, and is practically free from water.

(2) The experimental heading of the Channel tunnel, 7 feet in diameter, which commences at the foot of Shakespeare cliff close to the foreshore, and extends 1¼ mile in an easterly direction towards the Admiralty pier, Dover. This heading was practically impervious to water, and was driven during the years 1882 and 1883.

(3) A heading 12 feet in diameter driven in 1922 over the top of the Martello tunnel at the western end of Folkestone Warren. This tunnel was also quite impervious to water.

The level of the top of the chalk over the proposed site of the dock was known, and it was considered that it would be possible to construct the dock in the dry, although it was anticipated that a certain amount of pumping would have to be done.

When the work of construction was commenced the original intention was to contain the site of the dock within a cofferdam formed of a double row of steel sheet-piles driven into the chalk, stiffened at suitable intervals by steel diaphragms, thus making the dam into a series of boxes ; the spaces so formed were intended to be filled with chalk or other suitable material.

It was, however, found that the hardness of the chalk allowed only limited penetration with the piles, and when the first short length of sheeting had been driven, the piling was loosened to a considerable extent by the rough water before it could be properly stiffened. It was, therefore, decided not to proceed with this method but, by a slight modification in the design, to construct the enclosing walls of the dock in such a way as to enable them to act as a cofferdam.

Fig. 1, Plate 1, shows the plan of the scheme, from which it will be seen that the area in which the dock itself was to be constructed would be enclosed by concrete walls with an opening in a suitable position to form the entrance to the dock. This entrance would require closing temporarily, and it was anticipated that the enclosed area could then be pumped out to enable the construction of the

dock and pump-house to proceed in the ordinary way in the dry. Fig. 2, Plate 1, shows the sections of the enclosing walls, which are built on mass-concrete foundations about 1 foot thick and consist of pre-cast concrete blocks each weighing from 9 to 12 tons. In order to render them impervious to water-pressure, the joints are of the type known as "sausage" joints.[1] The method of bonding the blocks is also shown in Fig. 2, Plate 1.

In view of the pressures to be borne, coupled with considerable wave-action in stormy weather, much consideration was given to the method of temporarily closing the dock entrance, the probable alternatives being :—

(1) A horizontal arch of concrete blocks which could subsequently be removed.
(2) A horizontal steel arch.
(3) A steel caisson of rectangular cross-section.

Ultimately it was decided to adopt the third method, and it may here be briefly stated that the caisson was built at a shipyard on the north-east coast and towed to Dover, where at the proper time it was put into position and the entrance to the inner area sealed up. The caisson was provided with valves to allow of its being flooded as required.

The dock itself at its inner end is curved to fit the stern of the train-ferry vessels. Its depth is 45·72 feet and the general level of the dock coping is + 20·30 O.D. The dock bottom is at a level of —25·42 O.D. and this gives a depth of 3 feet of water below the vessel at the lowest recorded tide-level in recent years.

The floor of the dock is of concrete 5 feet thick. The ferry-vessels are connected to the shore by means of a link bridge of 70 feet span. The normal berthing level is + 6·5 O.D., and at this level the bridge is horizontal.

A longitudinal section of the dock is given in Fig. 3, Plate 1. The pump-house is situated on the north side of the dock in the position shown in Fig. 1, Plate 1, and the siding-accommodation which is being provided is also shown there.

The proximity of the Admiralty quay and of the entrance to the Dover Inner Harbour to the site of the dock necessitated the provision of an approach-jetty alongside which the ferries could first be warped before entering the dock. This jetty is 400 feet long and 30 feet wide.

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[1] These joints were first employed at Tranmere dock; see P. W. Bertlin, "Construction of the New Entrance to Tranmere Dock," Minutes of Proceedings Inst. C.E., vol. 221 (1925–26, Part I), p. 241.

Construction of Works.

Blockwork Walls.

The construction of the enclosing walls of the dock was the first portion of the work undertaken. The dredging or grabbing of the chalk to the approximate level under water was done by means of 10-ton electric derrick-cranes supported on piles driven in the sea-bed and so arranged that the cranes could command the whole site of the walls. The dredged bottom was levelled by divers, who then set old rails to the correct line and level of the underside of the first course of concrete blocks. Mass concrete about 1 foot thick was then laid by means of under-water bottom-opening skips, and divers guided the concrete into its correct position. When sufficient had been laid in this manner the surface was levelled by screeds which the divers manipulated on the tops of the rails. The blocks for the walls were then lowered into position by means of the derrick-cranes and were set by divers in the usual manner.

The block walls terminated in two massive heads at the dock-entrance, these heads being designed to take up the thrust of the gates and also temporarily that of the service caisson, and in order to ensure their complete stability all joints therein were grouted with strong cement grout. A mass-concrete sill 7 feet 6 inches thick was also laid by divers between the two heads, extending for a distance of 55 feet towards the inside of the dock, this sill being part of the permanent work (Fig. 3, Plate 1).

Concurrently with the construction of the walls the necessary dredging of the sea-bed at the approach to the dock to a depth of — 25·42 O.D. was put in hand. This proved to be very slow and difficult work, owing to the hard and consistent character of the chalk as well as the frequent heavy swell in the harbour. The buckets on the dredger employed were of ½ cubic yard capacity, and each bucket was fitted with two cast manganese-steel teeth which scraped out the chalk in shallow cuts. It was found only possible to dredge an average of 1,200 cubic yards per week, although the work proceeded night and day whenever sea conditions permitted.

When the outer walls were completed, the caisson was towed into position and gradually sunk by the admission of water. This caisson was 92 feet long by 60 feet deep by 28 feet wide, and weighed 525 tons. Vertical bearing-faces were formed in the heads of the dock-entrance, against which it would abut on either side, and a suitable face was also made in the concrete sill at the bottom of the dock for the horizontal bearing.

In order to form a seal, a limpet of oakum enclosed in a canvas covering was fastened to the three bearing-faces of the caisson

corresponding to the two vertical faces of the dock-heads and the bottom horizontal face of the sill. This proved very effective, and when the water-level was subsequently lowered in the enclosed area there was no discernible leakage at the junction of the caisson with the dock-walls.

Efforts were then made to pump the enclosed area dry with service pumps, but it was found that, although a head of from 12 to 20 feet could be sustained, the difference in pressure owing to the water in the enclosed area being pumped to a lower level than that outside caused an inflow of water through the sea-bed in the immediate vicinity of the works greater than the pumps could discharge. The usual methods of sealing such leakages by means of depositing mud and stopping up certain cavities which appeared were employed, but as they could only be used over a very limited area, owing to the adjacent entrance to the Dover Inner Harbour, they proved unsuccessful and did not result in any material change in the rate of inflow.

It was ascertained by means of colour tests that numerous fissures existed which were not of a character that could be stopped efficiently in the small area available for treatment. These colour tests were made by inserting small linen bags filled with permanganate of potash in fissures which were located by divers outside the enclosed area. The greater pressure outside forced the sea-water through the permanganate of potash, and the water thus coloured appeared at places inside the enclosed area. It further appeared that the employment of more powerful pumps might result in the enlargement of the fissures. Further, a much greater head of water, about 50 feet, would have had to be resisted to enable the work to be carried out in the dry, as compared with a maximum of 20 feet which had hitherto been maintained. With these considerations in mind, various other methods of carrying out the work were closely examined. A very ingenious way of carrying out the freezing process was devised by the specialists who were consulted, but it was felt that its doubtful success, coupled with the certain delay which would ensue, rendered it inadvisable to try this method. It was ultimately decided to devise special means for dealing with the more intricate portions of the under-water work and to carry out the works in the wet, constructing the dock, complete with the sill, floor and walls and also the adjoining pumping-chamber, without dewatering the site.

The first operation was the excavation of the chalk in the enclosed area. This was done by the dredger, and the work was carried out in two sections. The first section, which included the area on which the pump-house was to be constructed as well as the eastern half of

the dock-area, was done during the summer months with the temporary caisson from the entrance removed, and though progress was slow the work was satisfactorily accomplished at the rate of 1,200 cubic yards per week by working day and night when the weather allowed.

In order to secure the earliest possible completion of the works, it was necessary to proceed with as much of the permanent work as practicable concurrently with the dredging of the second section of the dock; the walls of the pump-house were therefore begun as soon as the site had been excavated.

Pump-Chamber.

The whole thickness of the pump-chamber walls could not be built in one operation, as it was necessary to lay and joint the cast-iron culverts forming the connexions between the pumps, the dock and the sea in the dry; in order to give the required space for this to be done, the first portion of the walls to be built had to be made 11 feet 6 inches less in thickness than was ultimately required.

Prior to the laying of any of the under-water concrete, experiments were carried out by making concrete blocks under water by means of a tremie pipe. A number of different brands of cement were tested and the results noted. As a result of these tests it was decided to employ ordinary Portland cement of a well-known brand using a 4-to-1 mix. A further experiment was made in one of the concrete piers of the jetty, which happened at that time to be under construction; in this experiment a cavity about 4 feet square was formed in the centre of the pier by means of shuttering. The level of the sea-bed at the pier was about the same as that of the underside of the pump-house floor, and the thickness of the concrete at the bottom of the cavity was 5 feet. This reproduced on a small scale the conditions which would exist in the pump-chamber, and, as the interior of the cavity remained dry under tidal conditions after being pumped out when the concreting of the pier had reached above high-water mark, the practicability of the method of construction adopted was demonstrated. The concrete was laid by means of under-water skips, which was also the method followed in constructing the pump-house floor.

In building the first thickness of the walls, the shuttering used so that the concrete could be deposited in the wet consisted of double rows of sheet-piling suitably braced together. It was impossible, however, to construct this shuttering except in perfectly still water, as the piles were 60 feet long and only penetrated 5 feet into the chalk. A very small disturbance of the water set up a swaying motion in the piling, and it therefore became necessary to close the dock entrance again with the caisson.

Before the caisson was replaced, the oakum limpet was removed and orifices between the caisson-faces and the dock-heads were so formed that, whilst the requisite amount of tidal water was allowed to pass without causing a "head" in either direction, any disturbance of the outer water was excluded from reaching the inner area. It was found by experiment that spaces 20 feet long by 14 inches wide at each vertical bearing-face produced the necessary conditions.

The remaining section of the dredging was then carried out with the dredger locked in the enclosed area, the spoil being removed by means of a crane fixed on a stage on the side of the area, which grabbed it from barges filled from the dredger and loaded it into trucks for disposal at a tip. By this means the dredging was much expedited, the output increasing from 1,200 to 1,800 cubic yards per week by reason of the calm conditions. At the same time as the dredging was done, the driving of the piling for the shuttering of the outer thickness of the pump-chamber walls proceeded. Accurate alignment of the piles was secured by pitching their toes against a heavy plate-girder placed under water on the correct line. When the outer row of piles of the pump-house chamber had been thus completed, the concrete floor of the pumping-chamber was constructed. It was necessary to design this of such a strength as to withstand the upward thrust of a head of 50 feet of water, and steel plate-girders 4 feet 6 inches deep and spaced at 4 feet between centres, each weighing 5 tons, were used to reinforce the concrete floor. The bearings for these girders were constructed by divers who fixed lengths of rails at the correct level on small piers of concrete-bag work placed on the chalk. A detail of this work is shown in Figs. 4, Plate 1. The reinforcing girders of the pump-chamber floor were lowered into place by means of cranes and adjusted by divers on the prepared foundations. The girders themselves were coated with cement grout before being lowered, so as to ensure watertightness as far as possible between the concrete and the steel when the heavy upward water-pressure of about $1\frac{1}{2}$ ton per square foot was subsequently taken. Twenty-one of these girders were used, as well as some smaller cross-girders at the sump end of the chamber.

The concrete between the steel girders was laid by means of under-water skips, the work being carried out continuously, and when the required amount of concrete had been deposited it was screeded off to the level of the tops of the girders. The bases of the steel piles forming the inner line of shuttering of the pump-house walls were stepped into steel channels secured to the upper flanges of the girders, as shown in Figs. 4, Plate 1.

The concrete in the side and end walls of the pump-chamber was

deposited through tremie pipes. Through these pipes the concrete can be passed to the required level under water, without contact with the water. In the use of the tremie pipe a ball is made of soft material, such as shavings with a cover of canvas, which accurately fits the interior of the pipe. It is inserted in the uppermost jointed length of piping, and concrete is then poured into the pipe (the top length of which is fitted with a hopper), forcing down the ball, which expels the water from the pipe in its descent, thus allowing the concrete to follow in the dry. The feeding-in of the concrete at the top must proceed continuously, and the bottom of the pipe must always be kept immersed in the concrete, the length of piping being raised gradually and shortened at the top end by the removal of the jointed lengths as the height of the concrete increases. Several tremie pipes are used simultaneously, their number depending on the amount of concrete to be laid; there is very little, if any, loss of cement from the mixture, and the properties of the resulting concrete are not affected. If the process of concreting is, however, suspended for any reason, laitance forms on the upper surface of the concrete, and before further laying is done this laitance should be cleared away.

From Figs. 4, Plate 1, it will be noted that special arrangements had to be made during the construction of the walls to provide for the junctions of the pump-culverts with the dock and the sea, and the scheme also provided for sluices at these junctions.

Owing to the limitations of space the outer thicknesses of the pump-chamber walls could not be made sufficiently strong to be stable as gravity-walls, and they were, therefore, strutted with a system of girderwork between the side and end walls. As a precautionary measure, the floor was loaded with 400 tons of concrete kentledge before the chamber was pumped out.

The outer thickness of the pump-chamber walls having been constructed in the manner described, the enclosed area was pumped out, leaving the chamber 103½ feet long by 39½ feet wide in which to carry out the work of constructing the culvert system and the various connexions to the pumps. During construction the sea-water was allowed to ebb and flow through two large-diameter pipes fitted with valves which were laid in the walls.

The method of construction of the floor and walls of the pump-chamber was found to have proved so successful that practically no pumping had to be done to keep it dry, percolation of water being confined to a few mere trickles, although, as previously mentioned, at high tide there was a head of approximately 50 feet of water.

When the culvert-system had been laid, concrete for the inner thickness of the walls was deposited in the dry; hook-end rods

1 inch in diameter, which had been previously left protruding through the inner skin of sheet-piling, served as ties to bind the inner and outer thicknesses together. The culverts were thus covered with concrete, and as the stability of the walls was by now ensured the temporary steel strutting was in due course removed and the construction of the pump-house and erection of the pumps was carried out at the same time as the construction of the dock itself.

For the culvert leading from the pumps to the sea, access to the sea had to be made by blasting a tunnel through the block-work cofferdam previously built; for this work a small steel sheet-pile cofferdam was constructed on the outside of the blockwork wall by driving the piles into the chalk, leaving sufficient space between the dam and the face of the wall to enable access to be obtained in order to blast away the concrete in the dry.

To withstand the upward water-pressure to which the bottom of this small cofferdam was subjected when it was pumped out, a reinforced-concrete floor was formed under water and the steel sheet-piles of the cofferdam were loaded with old rails as kentledge to prevent them being forced up. When the tunnel had been completed the piles were burnt off at sea-bed level, leaving the mouth of the culvert open to the sea. The opening for the culvert between the pumps and the dock was also made by burning off a section of the wall piling under water, suitable arrangements having been made in the dock-wall to allow of this being done.

Walls and Floor of Dock.

Similar methods to those employed for the pump-house walls were adopted in the construction of the main dock-walls, back and front shuttering being formed of two lines of Krupp sheet piling suitably braced together.

A gantry of Universal piles was driven along the site of the walls from a floating plant, and this gantry supported the back and front guide rails to which the shuttering was to be driven, the toes of the piles being pitched as before against heavy plate-girders placed under water on the proper line. The gantry also formed a staging on which to set the tremie pipes, and a second gantry of similar type was constructed from which the cranes could operate and along which the concrete could be conveyed in skips to the required position for pouring.

Between the two rows of Krupp-pile shuttering, at intervals of 40 feet, cross diaphragms were made of second-hand Larssen sheet piles which were available, and the walls were then constructed in sections in the boxes thus formed, each section being about 40 feet long by 28 feet 6 inches wide. Before the concreting of any section

was commenced, the bottom of that section was first thoroughly cleared of silt which had accumulated since the dredging took place; the concrete was then laid through the tremie pipes. The concrete mix used was 4 to 1 for the first few feet from the bottom, then 5 to 1 up to water-level, and finally 6 to 1 for the concrete placed in the dry. With the particular aggregate used, the concrete flowed under water to a slope of about 1 in 4. A temporary culvert was formed through the north and south side dock-walls so as to avoid any head being formed through tidal action whilst the concrete was being placed under water, and throughout the whole of the work consideration had to be given to the fact that upward water-pressure would be exerted if a difference of water-level were caused by any of the operations of construction. This was particularly the case with the pump-chamber.

The dock-floor, which is of mass concrete about 5 feet thick, has sufficient weight to withstand the greatest upward water-pressure to which the floor is subjected under maximum high-water conditions when the water in the dock itself is at berthing level. It was constructed in sections each about 20 feet wide and reaching from wall to wall of the dock. Construction was begun at the shore end, specially-constructed shuttering being placed across the dock at the edge of the first section to be concreted. Considerable silt had accumulated in the dock-area since the dredging had taken place; as much as possible was first removed by grabbing cranes, the final cleaning of the bottom being done by divers before any concrete was placed at any section of the floor. The concrete was then laid by means of under-water skips which were guided into place by the divers. When one section had been completed and the concrete had hardened, the shuttering was moved forward a length and the process repeated.

The filling around the dock-walls, amounting to about 45,000 cubic yards, was of Dungeness shingle, this material being very suitable for the purpose and having a satisfactory angle of repose, about 1½ to 1, under water.

Pump-House.

The pump-house is a steel-framed building, and, in order to allow of its being constructed as rapidly as possible and to avoid delay between the time of completion of the pumps and the time of completion of the dock, the walls were formed first of dovetailed-section steel sheeting. This gave the necessary protection from the weather so that the erection of the electrical and other portions of the pumping-plant could be carried out as early as possible.

While the pumps were being erected, brick facing walls were built

on the outside of the structure, the mortar of all the joints being keyed to the sheeting. The inner face of the steel dovetail-sheeting was subsequently plastered and the outer side of the brick wall coated with cement with a stippled finish.

The roof of the pump-house is of a patent metal type, covered with "Ruberoid," and was also designed to allow of rapid completion. Details of the pump-house construction are shown in Fig. 5, Plate 1.

Dock-Sill and Jambs.

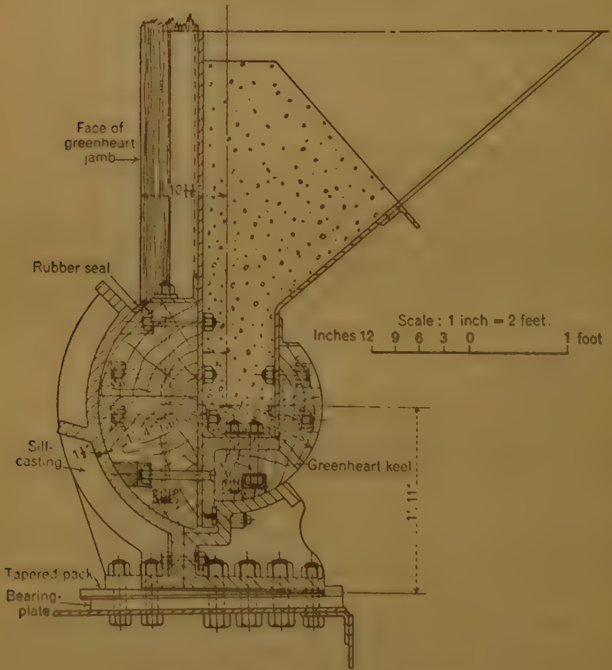
For these portions of the work it will be realized that the ordinary method of construction in concrete with granite bearing-faces for the dock-gates was not feasible with the under-water conditions prevailing. With dock-gates of the flap-door type, the horizontal hinges of the gates on the dock-sill must be accurately set in the bearings; the requisite degree of accuracy could not be obtained unless that could be done in the dry, which the conditions rendered impossible. Neither could the vertical bearing-faces have been constructed with the required degree of accuracy in granite. It was, therefore, decided to make this section of the work in the form of a U-shaped steel shell or pontoon. On the horizontal member of the U, which would form the sill of the dock, were placed the cast-steel bearings for the hinges of the two gates, the vertical sides of the U forming the jambs of the entrance. Details of this construction are given in Figs. 6, 7, and 8, Plate 2, and it will be noted that the bottom horizontal portion was made amply strong enough to prevent the possibility of deflexion to any appreciable extent during handling.

The lower portion of this, including the whole of the sill with the cast-steel bearings for the gate-hinges thereon, was built in the dry beforehand on a staging erected a short distance from its final position, and when ready was lowered into the water by means of hydraulic jacks after a suitable amount of concrete had been placed in its hollow sill for trimming purposes. Particular care was taken in the setting of the cast-steel bearings, tapered wedges and packing-pieces (*Fig. 9*, p. 236) being used in order to secure true alignment.

Two access-shafts, each 3 feet in diameter, were constructed from the top of the sill so as to allow the placing of further concrete therein, and also the fixing of flushing piping for the purpose of cleaning the bearings. This portion of the pontoon, with a floating weight of 800 tons, was afterwards towed to its final site in the entrance of the dock, the entrance-caisson having been moved to allow of this being done. The pontoon was then lowered on to its final bearings by the process shown in Figs. 10, Plate 2. It was held in position by guide-timbers and brackets which had been previously fixed to the

inner faces of the dock-walls, the temporary caisson being replaced at the entrance to the dock so as again to ensure still-water conditions in the enclosed area. In this position the upper parts of the two jambs were added length by length and the pontoon was gradually sunk and kept trimmed in a vertical position by the deposition of suitably-placed concrete in the sill. During the building-up process two old boilers were strapped to the pontoon, one on each side, to give added stability to it, and it was finally

Fig. 9.



KEEL AND HINGE OF DOCK-GATE.

sunk on to two grillage-foundations which had been formed on the sea bed, its weight at that time being 1,200 tons.

It was essential that the base of the pontoon and the bearings in the dock-gates should be accurately levelled, and special methods were adopted to ensure this. After removing the accumulated silt, therefore, from that portion of the dock-bottom on which the pontoon was finally to rest, concrete was placed on two areas on which the grillages were to be placed. The grillages were constructed of steel beams bolted together, and each grillage was provided with six large screws on which to stand. Before placing the grillages

under water two rigid light levelling-towers, built up of steel sections and high enough to reach above high-water level, were fixed to them (Figs. 11, Plate 2). The height of each levelling-tower was accurately measured and recorded, and the whole lowered on to the bottom. Divers then adjusted the screws bearing on the previously-laid concrete until the top of each framework was accurately levelled, and thereafter filled in the space between and underneath the steel beams of the grillages with concrete. When this was done the levelling towers were removed.

When the pontoon had come to rest on these foundations, further concrete was placed to fill the whole of the interior of the sill with the exception of an access-passage to the bearing flushing pipes, and at the same time the vertical sides of the pontoon forming the jambs were also filled solid with concrete, these jambs being subsequently embedded in the dock-walls. When completely filled the total weight of the pontoon and concrete was 4,500 tons.

There remained a space under the base of the sill of the pontoon, around the grillages previously mentioned, which required to be made solid; this was accomplished by introducing cement grout through a system of tubes which had been fixed in the pontoon during its fabrication (Fig. 7, Plate 2). The grout was retained in the required space beneath the sill by means of small walls of concrete which were built by divers round the horizontal sides of the pontoon after it had come to rest on the grillages.

Dock-Gates.

The gates of the dock are of the "Box" type, designed on the flap-door system; when open the outer one is resting on the dock sill and the other in a recess in the floor of the dock. Two complete gates have been provided, one of which falls outwards towards the sea and the other inwards towards the inner end of the dock. The gates are hinged at the bottom, and are raised and lowered by means of winches actuated by electric motors. The mass of each gate as it is being raised and lowered is counterbalanced by weights which move up and down in vertical shafts, so that if when a gate is being lowered or raised it should be struck by a wave, it would be held in balance by its own weight resting on the sill and by the balance-weights connected to the top. It was considered that leaf-gates or rolling gates would not be suitable under the conditions which prevail at Dover when being operated in rough weather, as during the process of being opened or closed there would be a period when they would be vulnerable to shock from heavy seas to a much greater extent than would be the case with the type adopted.

In any "Box" gates built previously to the work at Dover

pressure could only be taken on the outer face of the gates, so that the water-level had always to be higher on the outside of the dock. At Dover the gates were so designed that if one gate is damaged the other gate will be able to maintain the ferry-service ; it was therefore necessary that each of the gates should be able to withstand a head of water on either its inside or outside face. To provide for this, strut-gates were introduced which swing out from the dock-walls and strut the back faces of the gates as necessary under the required conditions.

The pull on the hoisting ropes of the gate-winches in calm weather under the worst tide-conditions is 45 tons per rope, each gate having two ropes. To cope with stormy conditions it was decided, as a result of experiments, to introduce a friction-clutch or brake in the main winch which would prevent the hoisting ropes from being loaded beyond 60 tons per rope. If the gate when being lifted under wave-action swings to the extent of inducing a loading of over 60 tons per rope, the friction-clutch allows a certain amount of rope to be paid out until the load falls below 60 tons, and the winches were designed to deal with this pull. The main motors will raise each gate in about 3½ minutes, but in case of any unforeseen failure of these motors smaller stand-by motors have been provided.

The dock-gates were erected on an area of land which was available on the new Clarence quay in the rear of the dock and was conveniently situated for launching them into the water when completed, and this work went on simultaneously with the construction of the pontoon. They were riveted, caulked, the wedging gear fitted, and the greenheart timber keels fixed and dressed, and were then launched over ways which carried them at high water into the outer portion of the Dover Inner Harbour. Details of the gates are shown in Figs. 6, 7, and 8, Plate 2, and in *Fig. 9* (p. 236) ; they weigh 300 tons each, and were made of steel with a copper-content of 0·25 to 0·35 per cent.

After launching they were carefully examined for any deformation which might have taken place during the launching process, but no defect whatever could be found. They were subsequently towed into the ferry-dock, and, before being finally fitted into their bearings, were placed in temporary upright positions on either side of the pontoon, as shown in Figs. 12, Plate 2, so as to form a cofferdam around the dock-sill to enable final checking and adjustment of the bearings to be made. This cofferdam also allowed access to the interior of the sill for completing the laying of concrete therein and fixing the gate-bearing flushing pipes.

In case it should become necessary at any time, arrangements have been made for pumping out the space between the two "Box" gates, and when the gates were in the temporary position referred to

above the final pipe-connexions from the dock-sill to the drainer-pump were made.

During this stage of the work the temporary caisson, which had been removed from the dock-entrance to permit the gates to enter the dock, was replaced, as it was of much advantage to secure still-water conditions in the dock-area.

When the space between the two dock-gates was pumped out it was found that the gate-bearing castings needed no adjustment, and it was also established that the base of the pontoon was level to within $\frac{1}{10}$ inch.

While this work was going on, the bearings for the strut-gates were fixed. It had been possible to provide for the inner pair by constructing their quoins as an integral part of the pontoon; for the outer pair, however, recesses in the blockwork on both sides of the dock-entrance had been made, into which the quoins could only be built in the dry. Two steel limpet cofferdams were, therefore, constructed and placed in position in front of these recesses and the water pumped out. The quoins were then set and concreted in, the limpets removed, and the strut-gates themselves afterwards adjusted accurately in position.

The last stage of the work on the erection of the dock-gates, namely, removing them from the positions in which they formed the temporary cofferdam and fitting them into their sockets on the sill, also took place with the temporary caisson still in position; as soon as this was accomplished the caisson was taken away.

Machinery-Pit Shafts.

Various deep shafts were constructed in the walls on both sides of the dock-entrance for housing the pulling-off weights and the balance-weights of the wave-action balancing gear for the gates, the gate-space drainer-pump and various float-level indicators. The general method of construction adopted was to suspend cylinders of cast-iron segments from staging in the water, these cylinders forming the shuttering for the shafts. Concrete laid through tremie pipes was then deposited around them, the segments being thereby incorporated in the walls and forming the lining of the shafts.

Link-Span Bridge.

Calculations and actual experiments with rolling stock showed that it was necessary so to design the lifting bridge as to allow for a maximum lateral slant of 2 feet 6 inches and a change in gradient of 1 in 35 for bogie coaches and 1 in 24 for wagons. This is due to the list of the vessel to one side or the other as vehicular traffic of varying weights is shunted to and from the vessel. The longitudinal

level of the ship also varies under these conditions, and it was necessary for the required degree of flexibility to be incorporated into the bridge. The structure was, therefore, designed with articulated joints at all its connexions, the main girders at the shore end working on horizontal pin bearings. Its carrying capacity is of the standard required to deal with the heaviest traffic on the railway. Details of construction are given in Figs. 13 and 14, Plate 3.

The free end of the bridge is suspended from links by which the span can be raised or lowered to the required angle. When in use the free end is lifted up to the necessary height to allow of the stern of the ferry-vessel being brought home to the curved inner end of the dock. This having been done, the starboard side of the vessel is held securely to the southern wall of the dock and the lifting bridge is lowered on to the stern of the vessel, a pin on the latter entering a socket formed in the end cross-girder of the bridge. Bearings are provided on the deck of the ferry on which the free end of the bridge rests, and a bolt actuated by a motor is inserted in a slot in the upper end of the pin which secures the bridge to the vessel. This bolt is interlocked electrically with the signalling apparatus for the two lines which lead on to the ferry-vessel.

The bridge is operated from a machinery-room situated immediately above it, and its weight is counterbalanced by kentledge which moves up and down two towers. It is raised and lowered by two independent sets of electrically-driven machinery, and in the event of failure of current the span and locking bolt can be operated by hand.

The motors have sufficient power to raise or lower the span through its working range in about 2 minutes. When the span is resting on the vessel it is freed from the machinery by clutches to allow it to follow the motion of the ship. The electrically-controlled equipment is duplicated, and an illuminated indicator shows the settings of the span, the locking bolt and the brakes and clutches in the machinery-house. A warning gong rings when the span is nearing the end of its permissible vertical travel, or when the amoant of lateral slant on it is approaching the maximum permissible. The reeving of the hoisting ropes is as shown in *Fig. 15*.

Approach-Jetty.

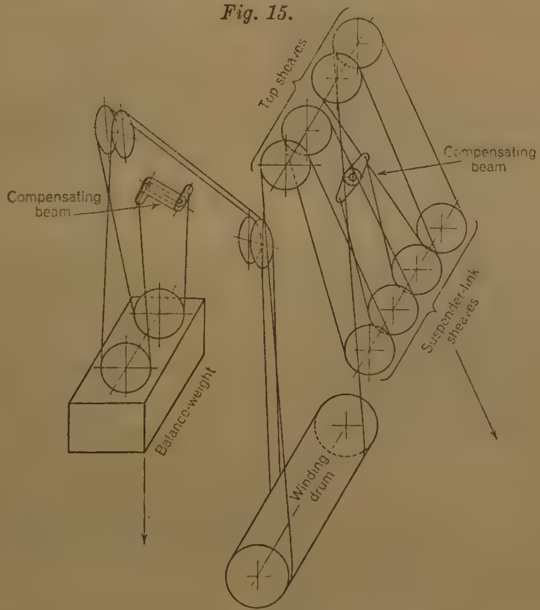
The main portion of the jetty is carried on rectangular concrete piers each 31 feet wide by 11 feet thick, spaced 11 feet apart. The inner end is of solid concrete for a length of 66 feet, whilst the pier at the seaward end has a shaped nose formed on its outer face.

The piers are connected together by two horizontal rows of ferro-concrete beams, the reinforcement of which is suitably connected

with the piers. The four piers at the shore end, where the foundations are at a lower level, were heavily braced together by diagonal rail ties encased in heavy sections of concrete to give resistance to the impact of ships. The jetty has a concrete deck 1 foot 6 inches thick, and is reinforced with steel beams which carry the rail-track thereon. Particulars are given in *Figs. 16*, p. 242.

In the construction of the pier a staging of piles diagonally braced together was driven by means of a floating plant. From this staging rectangular boxes of the required dimensions formed of Larssen steel piles were driven 5 or 6 feet into the chalk sea-bed. The boxes

Fig. 15.

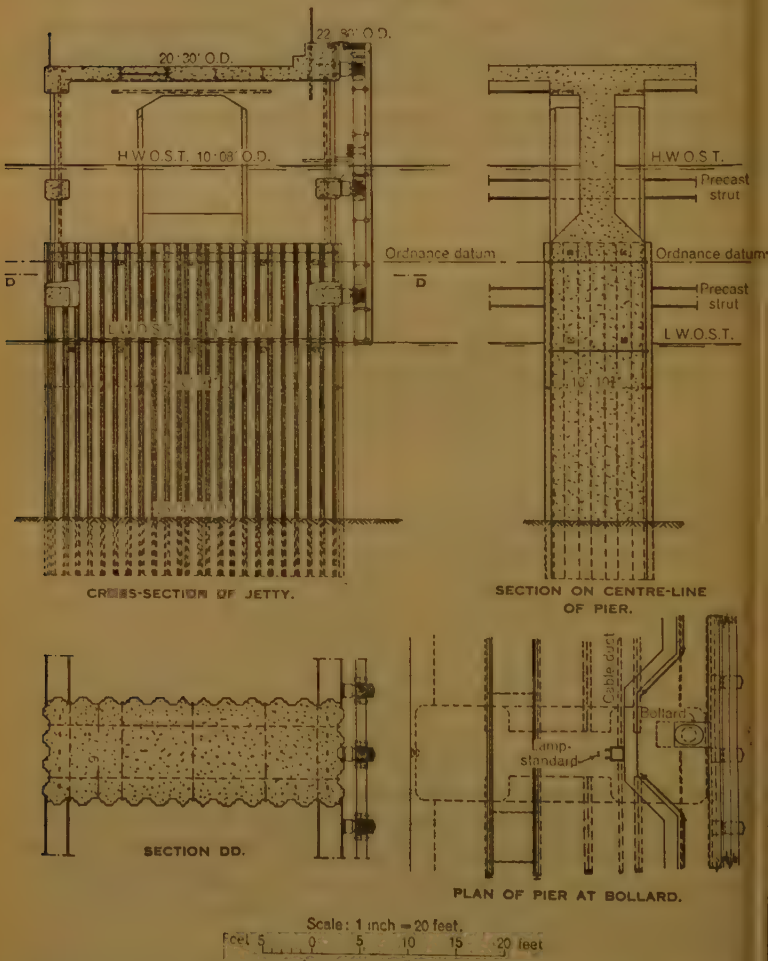


formed the shuttering for the mass concrete of the piers, and the sides of the boxes were connected together by tie-bolts, whilst heavy timbers connected to the staging and to the boxes gave support during the process of depositing the concrete. Rough weather on occasions made the holding of the sheet-pile boxes difficult, but it was generally possible to keep the work secure.

Once a pier was commenced, the concrete was deposited continuously from under-water skips to a point above low-water level, the upper portions of the piers to which the horizontal beams were connected being completed tidally in the dry. The concrete deck was constructed in sections which were securely dowelled to the piers by means of vertical rail reinforcement.

The berthing face of the jetty is fitted with fenders and rubbing-pieces, as shown in *Figs. 16*, and spring buffers working in cast-steel boxes are interposed between the backs of the fenders and the concrete work of the pier. Details of these spring buffers are shown in

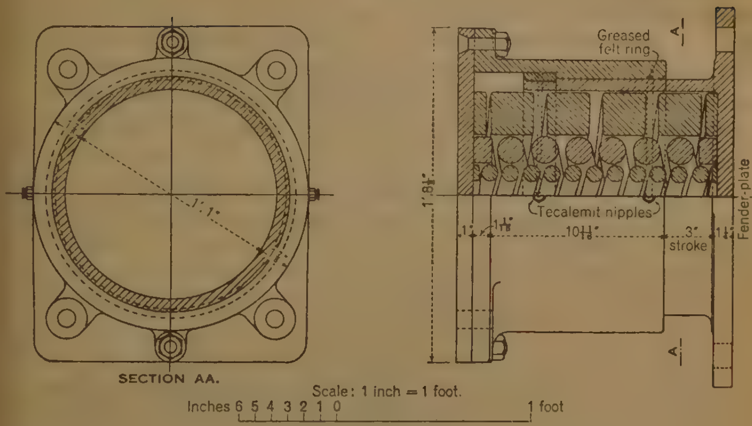
Figs. 16.



APPROACH-JETTY.

Figs. 17. The spring buffers allow a compression of 3 inches and the force necessary to produce this compression is 50 tons per buffer. Three springs of different diameters are concentrically arranged in the boxes and the space between them is filled with grease as a preventative of corrosion.

Figs. 17.



50-TON STEEL BUFFER.

Pumps.

The purpose of the pumping machinery is to adjust the level of water in the dock so that the train-ferry can be raised or lowered, as may be required, to the correct level to enable the link-span to be connected to the deck.

The functions required of the main pumping machinery, with its valves, are, therefore, as follows :—

(1) To pump water into the dock so as to raise the level should the vessel enter the dock at low tide.

(2) To pump water out of the dock to lower the level should the vessel enter the dock at high tide.

(3) To allow water to gravitate into the sea from the dock so as to lower the level when a vessel is due to leave the dock at low tide.

(4) To allow water to gravitate into the dock so as to raise the level should a vessel be due to leave the dock at high tide.

The arrangement employed is shown diagrammatically in *Fig. 18*, p. 244. From this it will be seen that there are two main culverts, one connected to the sea and one to the dock. These are 8 feet 6 inches in diameter, tapering down to 40 inches at the valves. There are twelve 40-inch electrically-operated sluice-valves, and three main centrifugal pumps, with 40-inch suction and discharge branches. In addition there are three 40-inch tilting-disk type reflux-valves connected to the discharge of each pump.

By this arrangement the pumps can be connected to perform either function (1) or function (2) mentioned above. For instance,

if it is desired to raise the level of water in the dock with pump "A," valves nos. 2 and 3 would be opened, valves nos. 1 and 4 remaining closed. The water may then pass from the sea culvert through valve no. 3, through the pump, the tilting-disk non-return valve and no. 2 valve into the dock culvert and thence into the dock.

In the same way pumps "B" and "C" may be connected with their appropriate valves.

The main pumps are of the centrifugal double-inlet type, and have 40-inch suction and discharge branches, the water entering

Fig. 18.

ARRANGEMENT OF DE-WATERING AND IMPOUNDING PUMPING PLANT.

both above and below the impeller. The plant is capable of raising the level in the dock by 16·4 feet in 30 minutes. This involves pumping 463,000 cubic feet with the three main pumps. Alternatively, the pumps can lower the level in the dock by 8 feet in 15½ minutes. The pumps have a maximum efficiency of 84 per cent., run at a speed of 250 revolutions per minute, and are driven by 230-b.h.p. motors.

Operation of the main pumps and valves must be rapid and accurate, and for this reason a supervisory control-system has been provided which enables a single operator to set the opening of the

valves in their correct order for any operation, without leaving the control-platform, and gives a visual indication on an indicator-diagram that the correct setting has been obtained.

Instruments are fitted on the control-desk which electrically indicate the sea-level, the level in the dock, and the rate of rise or fall of the water in the dock, whilst a special feature of the supervisory control is that, should any unit in the system break down, that unit can be isolated immediately and the remaining units continue to function.

An electric telegraph system is provided, similar to a marine engine-room telegraph, so that signals can be made to the pump-room operator from both ends of the dock.

Motor-Car Ramp and Drawbridge.

Facilities for garaging motor-cars have been provided on the upper deck of the train-ferry vessels, and this deck is approached by an incline on the north side of the dock. A short electrically-operated lifting bridge connects the top of this incline with the ferry.

New Clarence Quay.

In order to provide the necessary siding-accommodation for dealing with traffic to and from the train-ferry, it was necessary to reclaim 1·8 acre of land near the entrance to the Dover Inner Harbour. This reclamation is shown on the plan (Fig. 1, Plate 1). A cross-section of the new quay wall is shown in Fig. 2, Plate 1, the whole being constructed of pre-cast concrete blocks. There was no particular difficulty in regard to this work, as the chalk foundation was accessible at low water of spring tides. The new wall is 643 feet long, and is backed by a prism of hardcore for its entire length.

The filling between the old and the new Clarence quay walls is of Dungeness shingle, which was found very suitable for the purpose.

Conclusion.

The works were designed by and carried out under the direction of the Author. The Contractors were Messrs. Edmund Nuttall, Sons & Co. and John Mowlem & Co. (Joint) Ltd. From June 1935 Messrs. John Mowlem & Co. carried out the work for the joint firm, which was represented at the site by Mr. H. A. Henry, M. Inst. C.E.

Messrs. Coode, Wilson, Mitchell & Vaughan-Lee, MM. Inst. C.E., were consulted by the Author from time to time, and their assistance in connexion with the problems which arose was much appreciated.

Mr. Conrad Gribble, M. Inst. C.E., as Assistant Engineer for New Works and Bridges, Mr. M. G. J. McHaffie, M. Inst. C.E. who assisted

in connexion with the supervision of the work over a difficult period, and Mr. Frank Whyte, M. Inst. C.E., as Resident Engineer, should be specially mentioned.

Messrs. Sir William Arrol & Co. were the sub-contractors for the supply of the dock-gates, the link-span bridge, the special pontoon and other items of structural work, and were represented at the site by Mr. J. W. Sommerville, Assoc. M. Inst. C.E.

To those other gentlemen who were engaged on the work and who have assisted in the preparation of this Paper the Author tenders his thanks.

The Paper is accompanied by twenty-three sheets of tracings, from which Plates 1, 2, and 3, and the Figures in the text have been prepared, and by twelve photographs.

Discussion.

The Author.

The AUTHOR showed a number of lantern-slides and a cinemato-aph film illustrating the works described in the Paper. In con-xion with Sir John Fowler's scheme for a Channel ferry, referred on p. 223, it had been proposed to make a still-water harbour of out 95 acres; without wishing to criticize the proposals of so ustrious an engineer, he thought it probable that insuperable fficulties would have arisen in producing still-water conditions er such a large area at the Dover end of the ferry route, owing to e swell which was produced by the narrowing of the English annel in the neighbourhood. It would also have been difficult to nstruct the proposed lift-platform, 220 feet in length, to carry half train, so that it could tilt both longitudinally and laterally to the pe and list of the vessel as the latter was being loaded and unloaded. he vessel was to have had two sets of paddle-wheels, probably to sure as much comfort as possible in heavy weather.

He also referred to the trial heading of the Channel tunnel driven tween 1882 and 1883. That heading commenced at No. 2 shaft, st on the Folkestone side of Shakespeare tunnel, and extended in an most due easterly direction for a length of about 1¼ mile towards over. At No. 3 shaft, which was situated at the eastern end of akespeare tunnel, the base of the lower grey chalk was proved to at — 105 O.D., and the thickness of the stratum was about 230 et. Allowing for the dip to the east which existed in the stratum, e site of the train-ferry dock was well within that formation.

At Dover there was always the possibility that rough seas would experienced with very little warning. It was very difficult to ognosticate the weather conditions at Dover for more than a few urs ahead, and all the works had had to be designed with that enace in mind. The temporary caisson used at the dock-gates to ose the dock-area was a large and unwieldy structure, but it ould have been impossible to have carried out the work without it. e caisson had been removed and replaced about half-a-dozen times r various purposes during the course of the work, and had proved be of very great value. It would have taken very little movement the water to upset the steel sheet-piling used in the construction of e pump-chamber, but the water in the enclosed area had never ore than the slightest ripple upon it, due to the heavy throttling-wn of the tidal water between the temporary caisson and the dock-ads. The dimensions of the openings were, as stated on p. 231,

The Author. 20 feet long by 14 inches wide at each vertical bearing face, and was found that if they were made a little bigger, quite a mater swell was produced even inside the dock-area. The result of t wave-breaker, made with large concrete blocks, which had be built at the landward end of the north face of the Admiralty p (Fig. 1, Plate 1) had been, incidentally, to improve the berthing the Admiralty quay; it had damped down the swell which used exist, and it was now slightly easier for the masters of vessels to ber alongside that quay. Both sides of the train-ferry dock jetty could used for berthing purposes if the necessity arose in the future, t sea-bottom having been dredged to the necessary depth. For mo than 2 years the bulk of the work had been below sea-level, and considerable number of divers had been employed. Their work h been consistently good and in no instance had fault to be found wi them. He pointed out that it should be possible to operate the doc gates in any weather which would allow ships to come alongside t jetty, and they had been operated on occasions when there had be a swell of from 5 to 6 feet. An aerial photograph of the finish works was shown in *Fig. 19*, with one of the ferries in the dock.

The President. The PRESIDENT, in proposing a vote of thanks to the Author, sa that all would appreciate the dogged determination with which t Author and his engineers had continued to work in spite of ma adverse circumstances. The Paper had the merit of calling attenti to the difficulties encountered and not merely describing the results.

Mr. Wilson. Mr. M. F.-G. WILSON remarked that one of the most interesti features of the work described was the unexpected difficulty whi arose because of the large flow of water. He wondered where the water came from, because nothing had been said about borin nor whether the chalk at the bottom of the dock was thorough solid. There had been very large falls of cliff all along the coast various times, and there might have been loose chalk on the doc site. There was also an old river-bed somewhere in the vicini although he had never seen an accurate plan of it. Was it fresh salt water which had been encountered? The site of the work v very exposed, and there was salt water all around it. An importa section of the Admiralty harbour, Dover, for which his firm had be Chief Engineers and he himself had been Superintending Engine was the forming of a large reclamation area at the eastern end of t harbour. The retaining wall for that reclamation was founded the foreshore just above low-water level. The foreshore consist of hard chalk with many fissures, through which a considera quantity of water passed when the excavations were being carri out. In one case an exceptionally large spring of fresh water h been encountered, which was sufficient to supply the whole of t fresh water required for the greater portion of the work.

Fig. 19.

AERIAL VIEW OF TRAIN-FERRY AND DOCK.

It must have been very discouraging to the Author to have had Mr. Wilson. o carry out in the wet work which he had expected to carry out in he dry. The placing of mass-concrete under water was always ifficult, as the concrete could not be moved under water on account f the risk of washing out the cement, and much care had to be exerised in getting the concrete into place.

He was interested in the use of tremie pipes. The use of such ipes was quite satisfactory, but great care was required to see that he pipes were always full and that the ends of the pipes were always n the concrete; if the pipes were not carefully used they simply ecame shoots and the effect would be to allow the cement to be ashed out and to separate the coarse aggregate from the fine and so njure the concrete. Very careful supervision was therefore required he whole time in order to see that every shovelful of concrete got nto the right place. Concrete placed under water in the way escribed needed to be brought up continuously from the bottom o the top. A great deal of experience in that direction had been btained in Singapore when sinking cylinders under water which were lled with concrete. The necessity for bringing the concrete up in ne operation had not been fully appreciated and the work had been nterrupted, with the result that a great deal of laitance was found n the cylinders, sometimes amounting to from 8 to 10 feet, which had ll had to be cleared out before work could be started again. From the ay in which the work described in the Paper was carried out, hower, he assumed that that trouble had to a large extent been avoided.

Another very interesting feature in connexion with the Dover orks, which was also rendered necessary by the work having to be one under water, was the forming of the sill and the side-jambs in ne caisson and sinking it into place. That was bound to save a great eal of trouble and seemed to have been very satisfactory. All rough the work a great many special operations and devices had een necessary due to so many important sections of the work having be carried out under water.

Sir HERBERT WALKER remarked that he was not competent to Sir Herbert Walker. eal with the Paper from its technical aspect, but he did wish to say, a retired railway officer, that the thanks of the Southern Railway ere due to the Author for the way in which the work had been arried out. Sir Herbert had worked with the Author throughout at time, and he knew something of the difficulties which he had countered; in many cases those difficulties could not have been reseen, but the Author had adopted ingenious methods for overoming them and had brought the scheme to a successful conclusion.

The ferry was not a new departure in railway transportation, but e Southern Railway had not seen its way to carrying out the ferry heme from a commercial point of view so long as there was any possi-

Sir Herbert Walker.

bility of the Channel tunnel being made. As soon as it was definitel decided that there would be no Channel tunnel, the French Govern ment, acting through the General Managers of the French railway had approached the Southern Railway and had asked whether the would go on with the ferry, which they had agreed to do.

The ferry replaced a service of steam vessels which the Southe Railway had taken over 5 or 6 years ago, and which had been work at a very heavy loss. The ferry-service had only been in use f 12 months, but it had already turned that loss into a profit, and t difference between the loss and the profit which was now being ma was quite sufficient to return a reasonable rate of interest on t capital which had been expended.

Sir Henry Japp.

Sir Henry Japp observed that the Dover train-ferry dock had be a very difficult piece of work to construct. After the concrete-blo wing-walls had been completed and the steel caisson placed to cl the entrance, the pumps had been started and had discharged ov 1,000,000 gallons per hour, so that those concerned had been very su prised to find that at high tide the water gained on the pumps. Th was another large pump with a capacity of about 235,000 gallons hour which could have been brought into use, but as material w evidently coming out from under the dock-walls from the fissures the chalk, the Author had very wisely decided to stop the pumpi

The Geological Survey of Great Britain had been consulted, a had advised that the fissures were probably due to water runni down the chalk-surface, presumably feeding the river which at time had flowed on the site of the English Channel and had joi the Rhine in the bed of the North Sea. He himself could not recon the condition of the chalk with that theory. He thought that wh Mr. Wilson had suggested was more probable, the cliffs having fal down on the foreshore and great masses of chalk having be tumbled about by the waves and pounded for years, then hav been planed smooth by the millions of tons of shingle which w ever moving along the south coast of England, and the intersti having been filled with mud and powdered chalk.

When the pumping had been discontinued, the Author had be faced with the problem of redesigning the dock so that it could constructed in the wet instead of in the dry. The entrance h been open at that time, and the dredger was brought in to carry the excavation. The work had been pushed on at the site of pump-house, because it was estimated that the placing of the pu and culverts would take longer than any other part of the work, the Author had then saved a great deal of time by enclosing dredger within the dock and unloading the dredged material i Southern Railway trucks, so that while the pump-house was be constructed the main excavation for the dock was also proceedi

Sir Henry Japp.

ie fact that the pump-house floor, when it was de-watered, proved be almost entirely watertight, showed how carefully the divers d placed the concrete between the reinforcing-girders of the floor, iich were about 4 feet 6 inches deep and at 4-foot centres. The ock-walls themselves had been built by the use of tremie pipes, the ncrete having been conveyed to a hopper from which the pipes tered the water; as Mr. Wilson had said, the ends of the pipes were ways kept covered in the flowing concrete, and the work was rried on continuously. The laitance was negligible. It had been ped to deliver the concrete to the tremie pipes by concrete-pumps, it unfortunately the aggregate which was used consisted of crushed ingle with many sharp slivers of broken flints among it, which ere too much for the valves of the concrete-pumps; in fact, the rchase of new valves for the pumps cost nearly as much as the xing and placing of the concrete. The work of driving the fferdams commenced towards the end of 1933, and the dock was ened officially for public service on October 12th, 1936, only years afterwards. Considering all the difficulties which had had to met, that was a very short time, and the work had only been rried out in so short a time by the close co-operation of everyone ncerned, under the direction of the Author.

Mr. Hindmarsh.

Mr. R. F. HINDMARSH remarked that he was particularly interested the work described, because he came from Tyneside, where the rry-boats had been built to the design and under the supervision of r Westcott Abell, K.B.E., M. Inst. C.E., who himself had been con-cted for many years with Tyneside. Further, the "Box" dock-tes were the invention of Mr. Edward Box, M. Inst. C.E., an gineer closely connected with Tyneside for many years.

The blocks for the enclosing wall, shown in Fig. 2, Plate 1, had sausage" joints, and it would be of interest if the Author would say iether he had considered using rectangular blocks perhaps with le-joggles, caulking the face-joints, and grouting the internal nts solid with neat cement. There was always a difficulty in tting interlocking blocks such as were used in the present instance bed properly. The Author seemed to be satisfied with the sausage" joints, but there was bound to have been great difficulty making them water-tight, and in the case of any considerable ovement on the face of the wall and any slackness in the "sausage" gs, they would become loose very quickly owing to the movement the sea. Perhaps a single step in each course would have been fficient to have prevented any sliding of the blocks upon each other.

The Author stated on p. 228 that the dredged bottom under the ock-work walls had been excavated 1 foot lower than was necessary, d had then been built up again by concrete deposited under water d screeded off to the correct level by divers. Mr. Hindmarsh

Mr. Hindmarsh.

knew of at least three cases where a foundation of that sort had the course of years given trouble, and he would like to ask t Author whether the chalk could not have been dressed off to t correct level to receive the foundation-blocks by the use of divin bells, as had been done in the case of the Tyne and Dover brea waters. Possibly if that had been done an even more satisfacto foundation would have been obtained. The output of 1,200 cu yards dredged per week, working day and night, was, as the Auth said, very slow progress. Would it not have been possible to ha broken up the chalk in some way by explosive or rock-break preparatory to dredging?

The steel used for the dock-gates, containing from 0·25 to 0 per cent. of copper, was one which Mr. Hindmarsh had used in co siderable quantities, and whilst he believed that it did retard c rosion, he wished that an even more satisfactory material could produced at a price which would enable large quantities to be us in works of the kind described.

Had the steel buffers, filled with grease, on the face of the berth jetty proved satisfactory? What happened to the grease wh the buffers were squeezed up? There did not seem to be a outlet for it.

Mr. Maunsell.

Mr. G. A. Maunsell remarked that the outstanding feature interest, so far as he was concerned, was in connexion with cofferdams which the Author had described. The original intenti had apparently been that the whole area should be surrounded b steel-pile dam, but that intention had been abandoned and concr blocks had been employed instead. It was general experie that no two cofferdams were alike; each one required separa treatment. The peculiarity in the case of the dam described in t Paper seemed to have been the chalk sub-soil. That was a sta of affairs which might have to be dealt with again in simi circumstances somewhere else, and it would be very instructive if t Author could supplement the information already given by so details as to the behaviour of the chalk during the abortive atten at pumping. Dealing with the first attempt which was made to fo the steel-pile dam, the Author said that the chalk was very hard a that the piles could not be made to penetrate very far, whilst th was also the difficulty of the piles being loosened owing to the act of the waves. Farther on the Author said, however, that some p which had been put down for the purpose of shuttering the concr had been actually driven about 5 feet into the chalk. It seeme little difficult to understand how the chalk could have been so h in one place and yet fairly soft in another, and information on t variation would be of considerable interest.

With regard to wave-sway and its effect on piles, Mr. Maunsell

Mr. Maunsell. ently had experience of very similar circumstances in connexion h some of the foundations of the Storstrom bridge. In that case, steel-pile cofferdam had had to be put down in an open waterway out a mile wide which rapidly opened out on both sides, where re was quite a nasty short sea. The piles were put down in 30 feet water. There was no tide in the Baltic, and the first thing which s done was to put up timber-pile staging; above water a heavy ber waling was then constructed, and 20 feet below water a y heavy steel waling, elliptical in shape, was hung from the timber s. The steel piles which were put in were, be believed, of the e type as those that the Author had used, and of the same section. ey were rolled by Messrs. Dorman, Long and Co. Those piles e very satisfactory in every way, and in spite of the short sea serious difficulty from sway was experienced. The cofferdams e very expeditiously driven and were afterwards pumped out.

ir Henry Japp had thrown some light upon the block-dam ch was afterwards decided upon, and it would be very interesting know the actual reason why pumping had been stopped, because Paper stated that a difference of water-level of 20 feet between inside and the outside of the cofferdam had been obtained. The al experience was that when pumping had once been started and ery considerable difference in level between the outside and the de had been obtained, leaks tended to dry up, and by putting in reater number of pumps the area could be dried out. In fact, he fissures through which the water was coming could be regarded pipes, a very simple calculation would show that in the present only 50 per cent. greater pumping capacity would have been uired to dry out the whole 50 feet, as compared with what was uired for the 20 feet. There was probably some other reason, refore, which had prevented the pumping from being carried on, it would be very interesting to know what it was.

le had been interested to hear that the concrete which was put by tremie pipes had been so satisfactory, because some concrete that description had been placed in the foundations of the rstrom bridge. In order to ascertain whether or not the concrete good, a cylindrical shutter 3 feet in diameter and about 8 feet in gth had been fixed in a slanting direction in one of the blocks ch was going to be concreted under water. The concrete had n been filled in under water nearly up to the top of that shutter means of the tremie pipe, and when the concrete had set the space been pumped out, showing that there was about 3 or 4 inches of ance on the top. The shutter had then been broken out and it been possible to inspect the whole area of the cylinder where the crete had flowed around it. It was rather a good test of whether crete under water would actually flow around an obstacle and

Mr. Maunsell. make a good job, and it was found that the interior of that cylindri hole, 3 feet in diameter, was absolutely perfect; there was not a sp into which a finger could have been inserted.

Mr. Williamson. Mr. JAMES WILLIAMSON observed that he would confine his rema to one point only. A few years ago he had assisted in some sup vision in connexion with the train-ferry across the Yangtse-Kia between Nanking and Pookow. The conditions there were v different from those at Dover. The rise in the river in summ time, when the snows had melted and the flood-water was com down, was very great, and that meant that on each side of the ri there had to be four long lattice-girder spans, all capable of be inclined simultaneously to get down or up on to the ferry-bo The range of river-level provided for was 25 feet. From the end the last span there was an apron such as was shown in Figs. Plate 3, and it was to that apron that he wished to refer.

In the case of the ferry-steamer at Dover, there were two tra going on to the ferry, and they spread into four on the vessel. the case of the Chinese ferry, however, there was one track com down three of the approach-spans, but on the last span it branc out into three, and the apron and the boat had three tracks. It not quite so long as the apron at Dover, but the difference was follows. In the case of the Dover apron, which was similar to th for the Government ferry-boats run during the War, the construc was hinged and the cross-girders were hinged to the side-girders described in the Paper. The contractors for the Chinese ferry-bo however, had considered that it might be possible to make a sa factory apron without hinges at all; that was to say, with the cr girders and the stringers riveted. Calculations had been put forw for that arrangement which seemed to show that it should be flex enough to accommodate itself to the vertical movement, lateral ing, and fore-and-aft slope of the vessel during all conditions of l ing. The calculations had been complicated, and perhaps some those who had had to deal with the matter had not been too confid that they were right, so that it was arranged that the work shoul put together in the shops and tested there. The result of the test been to show that that apron—wider than the Dover apron, three tracks instead of two—would be absolutely satisfactory with any of the hinges at connexions between the cross-members and main girders or between the stringers and the cross-girders. apron was, of course, hinged at the shore end for lifting manœuvring. It had proved entirely satisfactory in service.

Mr. Wentworth-Sheilds. Mr. F. E. WENTWORTH-SHEILDS noticed that the Author had both underwater skips and tremie pipes for depositing conc under water, and that it did not appear that he had any sp preference for one method as compared with the other. Mr. W

orth-Sheilds's experience had been that depositing with skips Mr. Wentworth-Sheilds.
d not give satisfactory work, because of the great amount of laitance
oduced, as the Author had pointed out. If he had understood the
per rightly, hardly any laitance had been produced with the tremie
pes, provided that they were properly used. He understood that
e pump-house floor, however, which undoubtedly was very
ccessful, had been deposited with skips, and he would like to know
w the Author had managed to get rid of the laitance and to make
ch a fine job.

Could the Author prove that there was any real advantage in
vering the steelwork with grout before depositing the concrete?
was difficult to imagine that it could be advantageous, but no
ubt the Author had some good reason for adopting that method.
e Author had mentioned that several brands of cement had been
sted, and it would be of interest to know what qualities the successful
and possessed. Mr. Wentworth-Sheilds had found that for under-
ater work a coarsely-ground cement was far better than a finely-
ound cement, because it did not produce so much laitance, which
s only natural; but he would like to know whether that was the
ly feature of the brand which the Author had adopted or whether
had some other feature which was of advantage.

Finally, he would be interested to know why Krupp piling had been
opted in preference to, say, Larssen piling. So far as transverse
rength was concerned, he believed that the Larssen piling was
ther better than the Krupp pattern.

*** Mr. A. H. Case observed that, without wishing to reiterate Mr. Case.
tails of a work done long ago, it might be well to mention, in sup-
rt of what had been said about pumping as an alternative to
acing concrete under water, the similar difficulties that had been
countered when putting in the foundations of Beachy Head
hthouse, which had been excavated in chalk in the same formation
that at Dover in the sea-bed off Beachy Head. The foundations
re enclosed with a half-tide circular concrete dam, with a brick-
ed vertical inner face, and the idea had been to start pumping as
n as the ebb-tide was below the level of the top of the dam, and
us to be able to carry on the work of excavation and subsequent
ilding during the period of half ebb-tide to half flood-tide. In
actice, however, it was found during excavations that the chalk
d so many fissures—some of considerable size—in it that the pumps
re hopelessly inadequate to cope with the inflow of water during
b-tide, and no real commencement of actual work could be made
til the tide had ebbed far below the top of the dam. It was found

*** This and the succeeding contribution were submitted in
iting.—Acting Sec. Inst. C.E.

Mr. Case.

that during the flood-tide the pumps could cope with the inflow ar so could permit work to be continued until the rising tide had reach the top of the dam; that was probably accounted for by the pum having to some extent drained the surrounding chalk during ea period of work, whereas in starting pumping on the ebb-tide the cha and fissures were saturated. A great deal of time and expense w lost owing to that difficulty, and considerable delay was experienced the execution of the work, whilst it was too late, even if it had bee permitted, to substitute mass-concrete deposited under water f granite masonry; the latter, being of carefully-dressed grani with both horizontal and vertical dovetail joints, had to be built the dry.

He gave that information with the object of endorsing what t Author and Sir Henry Japp had stated with respect to the fissur character of the chalk. At Beachy Head, as at Dover, a boring h been sunk in the first instance to investigate the character of t chalk, but the boring had showed it to be solid and had given litt information as to fissures.

Dr. Brysson Cunningham.

Dr. Brysson Cunningham observed that the general excellen of the Paper made him regret that there was such an importa omission as all reference to the cost of the undertaking. In vi of the difficulties encountered, the cost was bound to have be considerable, although no doubt it could be urged that the circu stances were exceptional to such a degree that any particulars cost would be of little service for comparison with construction work elsewhere. At the same time, it was always useful to ha records of actual cost, and the value of the Paper would be mu enhanced if the Author would give some details of the expenditu incurred, particularly in regard to the under-water work, which h been carried out by two distinct methods, namely by the use bottom-opening skips and of tremie pipes.

With regard to the deposition of fluid concrete under wat most engineers would be disposed to agree in the desirability avoiding it wherever possible. The method at Dover seem to have been remarkably successful and the excellent results obtai should do much to reassure those who mistrusted the process. wondered how the levelling of the surface of the concrete floor screeds had been carried out without weakening the cement-cont of the fluid mass, and whether or not the disturbance of the deposi material had appreciably clouded the view of the divers.

He would like to ask whether much mud had been found deposi on the floor of the entrance where the gates rested in the open p tion, and by what means it was ascertained that the gates were ly below sill-level, so as not to run any risk of fouling the keel of a ve entering the dock.

Dr. Brysson Cunningham.

In view of the opinions expressed by Sir Robert Hadfield and Mr. ain in their Paper on the "Corrosion of Iron and Steel," [1] the alue of a copper-content of the order of from 0·25 to 0·35 per cent. the steel for the dock-gates was problematical. Dr. Cunningham ad employed similar copper-steel for sheet-piles driven in the hames estuary, but he had also taken the precaution of coating em with tar, as until further research had been made, the evidence the efficacy of copper as a rust-resisting ingredient for steel in arine situations was not conclusive.

The Author.

The AUTHOR, in reply, stated with regard to the question of borings at a preliminary boring had been made on the landward end of e dock. The whole area of the dock at the beginning of the work d also been pricked over with steel sheet-piles which had been iven to refusal to ascertain what variation, if any, there was in the ality of the chalk. Generally speaking, those prickings had shown ry consistent penetration, and hard driving had been necessary get the piles down some 5 feet. There were one or two small areas here the piles went deeper than was normal, and that was found be due to potholes in the top surface of the chalk on the sea-d, which existed just as they did in the chalk on the high cliffs tween Folkestone and Dover, where the top of the chalk was not solutely level but contained occasional potholes. When the ouble due to the percolation of water occurred, although there d been nothing to indicate either in the dredging which had ken place or in the prickings or in the excavations for the outer alls that such trouble would be met with, he thought it wise to ake a series of eight borings, locating the boreholes at those places here there was evidence of percolation visible on the water-surface the enclosed area. In one of these borings at some little depth layer of wet sand about 5 feet thick was reached. In other aces the borings showed perfectly solid chalk. Why that sort variation occurred at that place was, he thought, beyond the wer of geologists to explain.

As to whether the percolation-water was fresh or salt, in the course the work one or two springs of very cold fresh water had been und, but the percolation-water was undoubtedly sea-water which me through the fissures from the outside. Referring to the question to why pumping had not been continued when a head of 20 feet water had been held, after a prolonged period of continuous mping at the rate of about 1,000,000 gallons per hour it had been und that not more than a 20-foot head of water could be held, and at only for a short period. Many barge-loads of mud were posited to try to seal up the interstices which existed, but the

[1] Journal Inst. C.E., vol. 3 (1935–36), p. 3. (June, 1936.)

The Author. amount of percolation remained unchanged. The pumping had be stopped because it was thought quite possible that if it had be continued the chalk would have blown up under the complet outer walls, as the water boiled up in some places quite heavi Apart from that, there was the question of expense, as heavy co tinuous pumping of the order mentioned was very costly.

With regard to the placing of concrete under water, Mr. Wentwor Sheilds had asked why the underwater-skip method of placing t concrete in the pump-chamber floor had been adopted. It would found on reference to the drawings that each of the rectangu spaces between the girders of the floor was about 40 feet long 4 feet 6 inches by 4 feet, and those spaces were filled up one at time with concrete. For that particular work skips were the m convenient, and the concreting did not cease until the whole of ea space was filled up in one continuous operation. He had thoug that it would be a suitable precautionary measure to give a ceme wash to the girders beforehand, as if there were any tendency the concrete to shrink away from the steel girders the ceme wash given to the steelwork might form a key there. In the res the whole operation had been very successful.

As to which was the preferable method for depositing concr under water, by tremie pipes or by underwater skips, he thought t with large masses it was better to use tremie pipes, which enab concrete to be deposited simultaneously with any suitable numbe pipes, the discharge from the bases of which enabled a homogene mass to be built up. If the work were kept going continuously th was not time for laitance to form until the whole mass had b placed. Generally speaking, the best method to adopt depended the conditions to be met with in each case.

In regard to the question of rectangular joints and "sausag joints, the latter were very successful, as he had never found leakage through them, and the cores, which were enclosed in canvas tubing, did not seem to work loose. The joints seeme be doing everything that was expected of them.

The rate of dredging had been low, but Dover was a place wh the conditions were extraordinarily difficult. There were m periods when the dredger could only work for perhaps one or two d per week. The dredger-buckets were fitted with manganese-s teeth attached to the lips to loosen the chalk, which was very h but the buckets came up with only a few shovelfuls of materials time, although the dredging vessel employed was a stout one. trial was made with a more powerful dredger but the results were so satisfactory. Blasting operations and the employment of r breakers had been considered, but as the entrance to the Do Inner Harbour had to be kept safe and free from interrupt

blasting was not permissible in the outer area where the rate of dredging was the lowest. A rock-breaker had been tried, but it was found to be ineffective in improving the rate of progress. As mentioned in the Paper, blasting was employed in making the egress-channel from the pumps to the outer water, but very small charges were used there in a confined space. A considerable amount of heavier blasting was also done in the inner area in removing a mass of old brickwork and stone structures which existed on the site of the lifting-bridge foundations. Really heavy blasting was not, however, permissible, because of the possibility of causing damage to structures in the vicinity, and in any case it would have been of very doubtful advantage. The rate of dredging was the best which could be done under the conditions existing, and was improved by 50 per cent. in the inner dock, where swell conditions were eliminated. Considering the hardness of the chalk he thought that the rate of progress had been good. The Author.

In reply to Mr. Hindmarsh, he would point out that in a number of cases where it had been possible to make a subsequent examination of the concrete placed under water, it had been found to be consistently good and equal to concrete placed in the ordinary manner. That was noticeably the case when excavating for the egress-channel from the pumps to the outer sea (which channel passed under the north wall), and also in the pump-chamber itself.

The use of diving bells, which would have involved heavy lifting appliances, had been considered, but that method would have been far more costly and would have slowed down the rate of progress considerably.

The steel buffers filled with grease on the face of the berthing jetties had proved quite satisfactory, and the Author had used the same method on the reinforced-concrete landing stage at Portsmouth Harbour some 5 or 6 years ago, where they were also giving every satisfaction. The grease which was put in the buffer-casing was, of course, not packed in, nor did it act as in a dashpot.

Regarding Mr. Maunsell's remarks on the Storstrom bridge, the Author thought that the conditions at that bridge were not comparable to those at Dover, for the reason that at the latter place on a number of occasions heavy swells producing waves from 12 to 16 feet high were experienced, and it was a common occurrence for there to be a swell of from 5 to 6 feet. Moreover, whilst there was no tide in the Baltic, there was an average range of tide of approximately 18 feet at Dover, which on many occasions during the spring tides was exceeded; indeed, the ultimate range of 25 feet was experienced during the course of the work.

In constructing the piers of the jetty, the bulk of which was done during the summer months, although the steel boxes for the shuttering were provided with heavy walings, as well as being

The Author. braced to heavy staging, they were smashed in on more than on occasion during rough weather.

The Author was interested to hear of Mr. Williamson's experienc with the type of girderwork described across the Yangtse Kian between Nanking and Pookow. It was bound to follow, however if a bridge was put "in winding," as was the one at Dover whe loading and unloading of traffic was taking place, unless provisio were made for movement at the joints of the cross-girders with th main girders and railbearers, that there would be heavy and incal culable stresses put on such joints, which in the course of time woul lead to trouble. Perhaps, however, the conditions described by M Williamson were not similar to those at Dover.

Replying to a further point raised by Mr. Wentworth-Sheild the Author would emphasize that to avoid the formation of laitanc with under-water concrete, the whole of the concrete had to b deposited at one time to a point above low-water level. If an laitance formed on the top during tidal conditions it could afterwar be easily removed. The cement used had no special characteristic Krupp piling had been used because it could be obtained quick than Larssen piling, and because weight for weight it had a high transverse strength.

Mr. Case's notes regarding the construction of Beachy Hea lighthouse were instructive, but it was within the Author's knowled that a considerable amount of work in the chalk many feet belo low-water level had been carried out in the dry in connexion wit the docks in the Dover Inner Harbour, although owing to the eastwa dip of the strata the lower grey and more impermeable chalk shou there be at a lower level than was the case at the site of the ferry doc

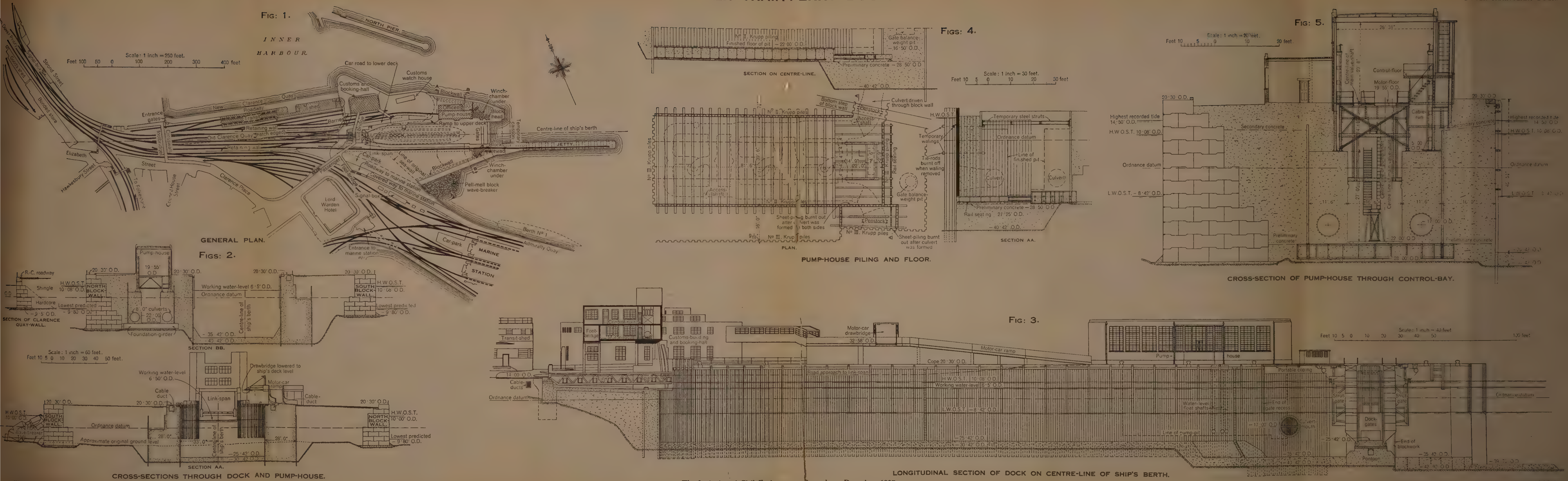
It was regretted that the costs regarding the work could not at present given as suggested by Dr. Brysson Cunningham.

The screeding of the surface of the concrete floor was done with ir straight-edges worked on the top of old rails previously set at t required levels. The disturbance, if any, of the deposited material ha not clouded the view of divers, as in any case the water was opaq

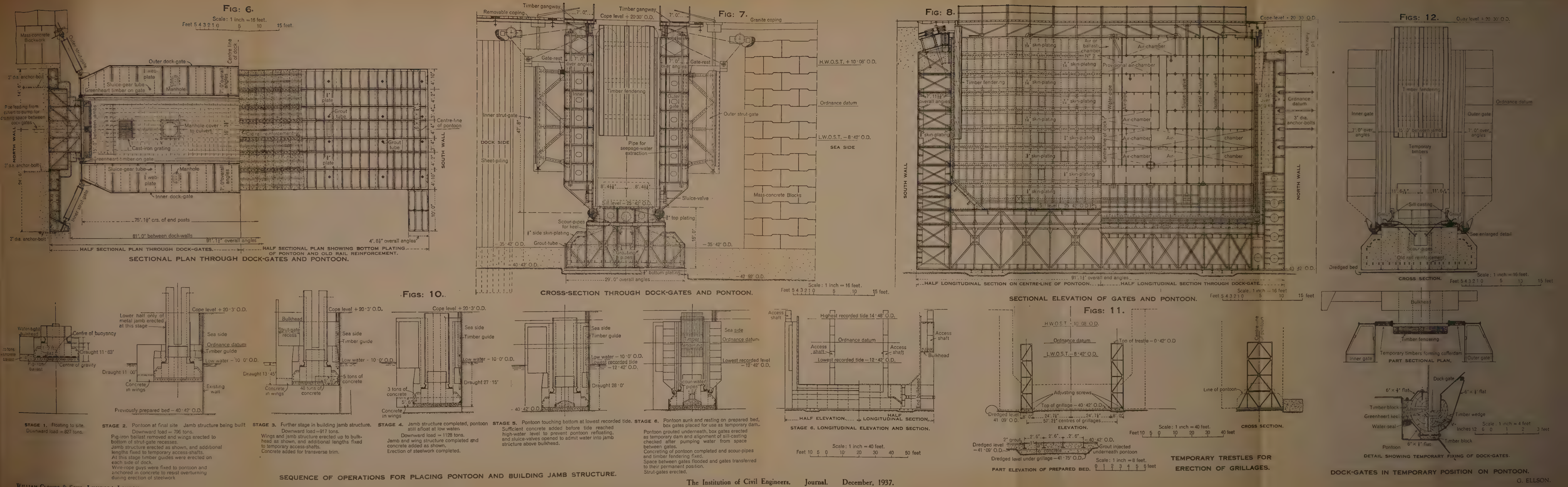
Very little mud accumulated on the floor of the entrance, owing the heavy scour which was caused when the ferry vessels left t dock. There was an indicator in the gate-control room which show the exact position of the gates at all points during their loweri There was an excess weight of 50 tons over the buoyancy of ea of the gates to ensure that they would lie on the bottom. All t steelwork used under water had been coated wherever possible wi tar or with suitable paint as a protection against corrosion.

*** The Correspondence on the foregoing Paper will be publish in the Institution Journal for October, 1938.—ACTING SEC. INST. C.

DOVER TRAIN-FERRY DOCK.



DOVER TRAIN-FERRY DOCK.



SECTIONAL PLAN THROUGH DOCK-GATES AND PONTOON.

CROSS-SECTION THROUGH DOCK-GATES AND PONTOON.

SECTIONAL ELEVATION OF GATES AND PONTOON.

DOCK-GATES IN TEMPORARY POSITION ON PONTOON.

STAGE 1. Floating to site. Downward load = 827 tons.

STAGE 2. Pontoon at final site. Jamb structure being built. Downward load = 796 tons. Pig-iron ballast removed and wings erected to bottom of strut-gate recesses. Jamb structure erected as shown, and additional lengths fixed to temporary access-shafts. At this stage timber guides were erected on each side of dock. Wire-rope guys were fixed to pontoon and anchored in concrete to resist overturning during erection of steelwork.

STAGE 3. Further stage in building jamb structure. Downward load = 917 tons. Wings and jamb structure erected up to bulkhead as shown, and additional lengths fixed to temporary access-shafts. Concrete added for transverse trim.

STAGE 4. Jamb structure completed, pontoon still afloat at low water. Downward load = 1128 tons. Jamb and wing structure completed and concrete added as shown. Erection of steelwork completed.

STAGE 5. Pontoon touching bottom at lowest recorded tide. Sufficient concrete added before tide reached high-water level to prevent pontoon refloating, and sluice-valves opened to admit water into jamb structure above bulkhead.

STAGE 6. Pontoon sunk and resting on prepared bed, box gates placed for use as temporary dam. Pontoon grouted underneath, box gates erected as temporary dam and alignment of sill-casting checked after pumping water from space between gates. Concreting of pontoon completed and scour-pipes and timber fendering fixed. Space between gates flooded and gates transferred to their permanent position. Strut-gates erected.

SEQUENCE OF OPERATIONS FOR PLACING PONTOON AND BUILDING JAMB STRUCTURE.

STAGE 6. LONGITUDINAL ELEVATION AND SECTION.

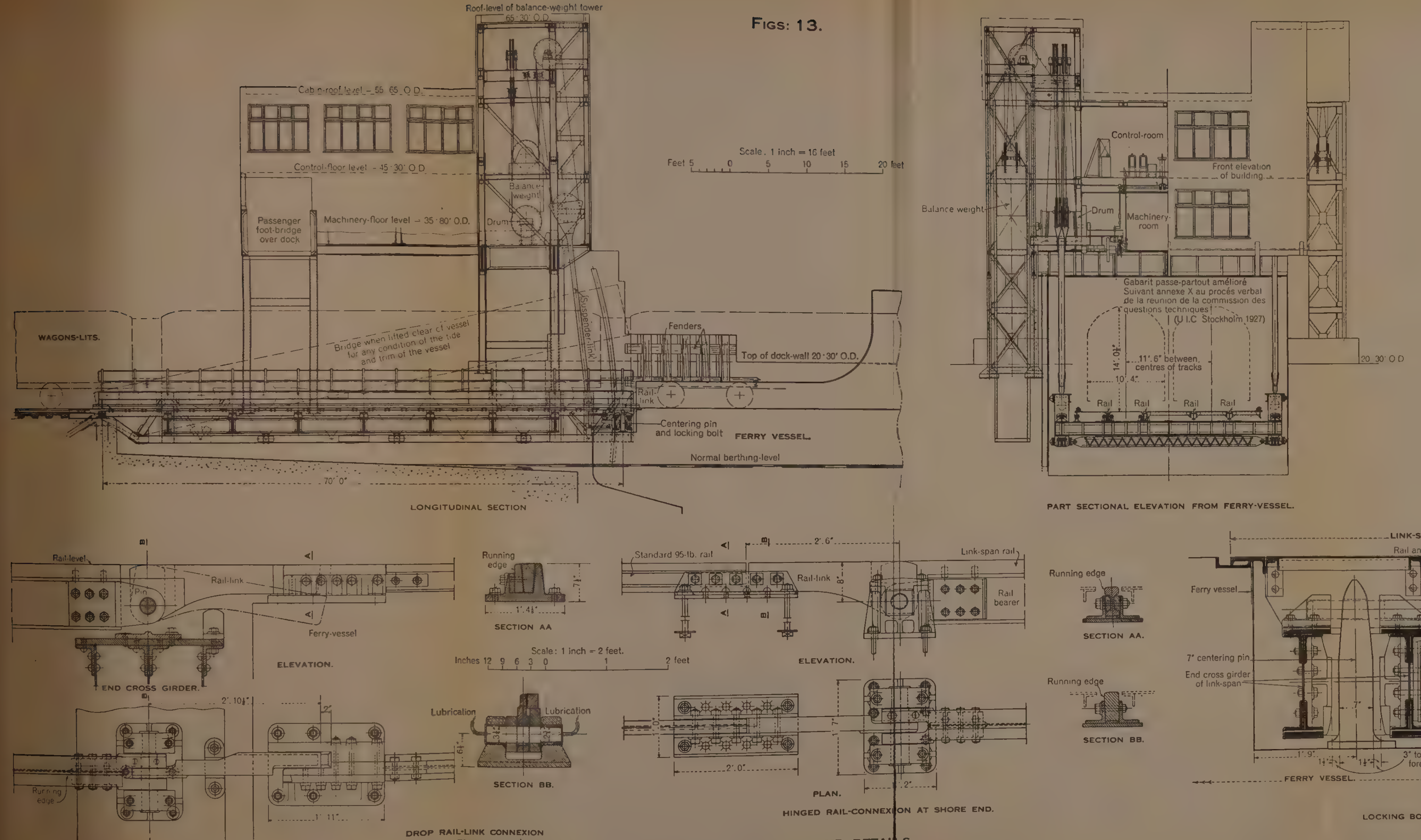
PART ELEVATION OF PREPARED BED.

TEMPORARY TRESTLES FOR ERECTION OF GRILLAGES.

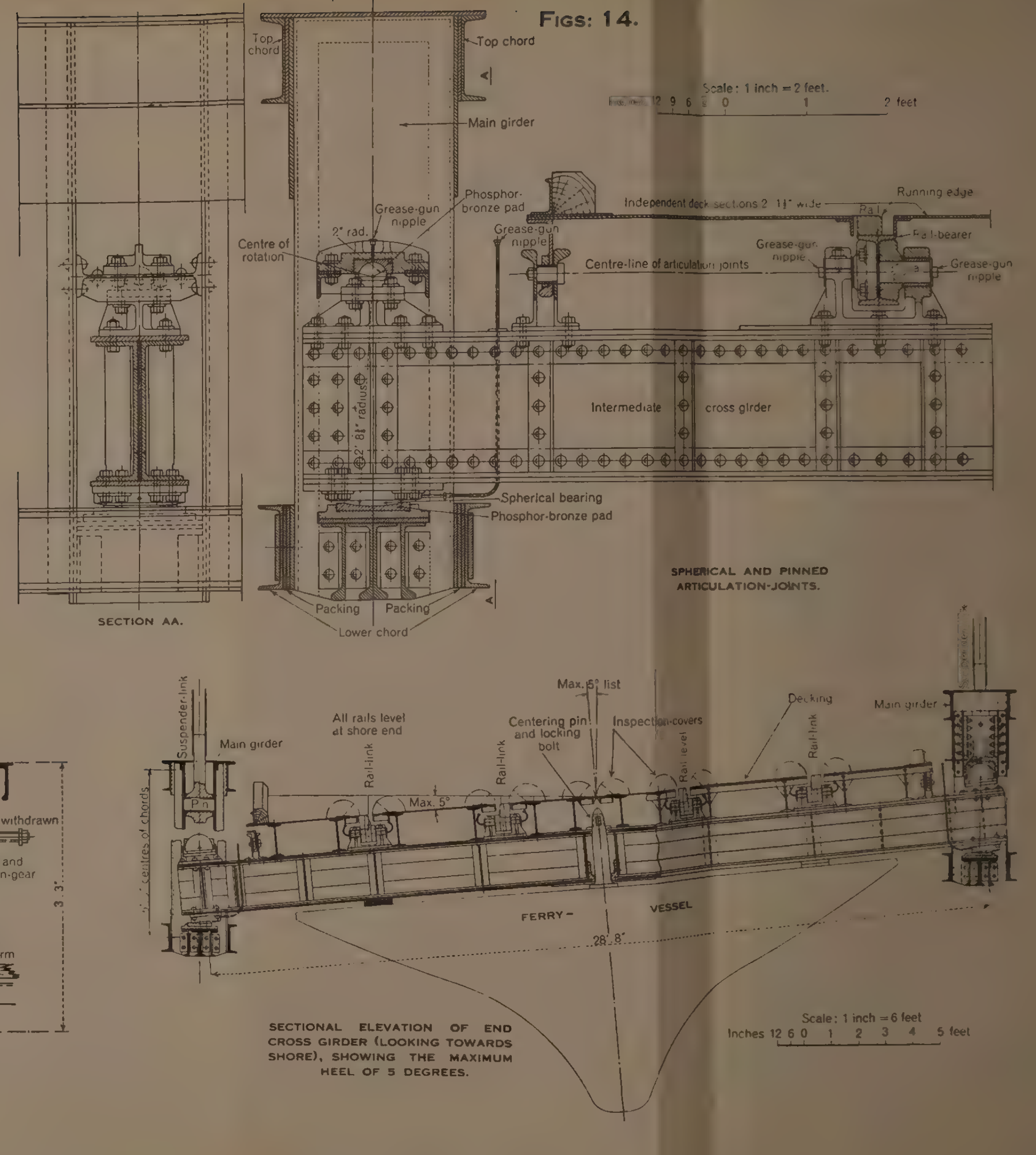
G. ELLSON.

William Clowes & Sons, Limited: London

DOVER TRAIN-FERRY DOCK.



LINK-SPAN AND DETAILS.



ARTICULATION OF LINK-SPAN.

Paper No. 5079.

"The Effect of the Form of Cross-Section on the Capacity and Cost of Trunk Sewers.

By Thomas Donkin, Assoc. M. Inst. C.E.

(Ordered by the Council to be published with written discussion.) [1]

TABLE OF CONTENTS.

Introduction.

When considering the design of a trunk sewer, the usual practice is to use either a circular or an egg-shaped form of cross-section, the choice between the two being determined usually by the general gradient of the particular length of sewer under consideration. It is usual, in cases where the gradients are reasonably good, to adopt a circular form, the egg-shaped form being used in cases where it is desired to obtain better self-cleansing velocities on account of the flatness of the gradient.

It is proposed to discuss the relative merits and costs of both these forms of cross-section, together with those of another form of cross-section, which may be called a U-shaped section. This so-called U-shaped section in its fundamental form has a semicircular invert with vertical side walls and a flat top, within which may be inscribed a circle of the same radius as the invert. Three forms of this particular type of sewer will be considered in two different proportions of height to width.

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[1] Correspondence on this Paper can be accepted until the 15th March, 1938, and will be published in the Institution Journal for October, 1938.—Acting Sec. Inst. C.E.

Accepted Method for Calculating Velocity and Discharge.

The accepted method of calculating the velocity and the discharge of any sewer or open channel, no matter what its form of cross-section may be, is by means of an expression of the following form :—

$$V = CM^xI^y,$$

where V denotes the average velocity,
M „ hydraulic mean depth,
I „ inclination or slope,
and C is a constant.

From this it is obvious that the average velocities of discharge vary in direct ratio to the slope raised to the power y and to the hydraulic mean depth raised to the power x. It will thus be seen that the form of cross-section is independent of the constant and the slope, and that for equal slopes the velocity is directly proportional to the hydraulic mean depth raised to the power x. Since the discharge is obtained by multiplying the average velocity obtained from the above expression by the cross-sectional area of the sewer, it follows that the discharge is also directly proportional to the particular form of cross-section under consideration.

When calculating the size of any particular type of sewer, a gradient is first of all assumed, from which the size is obtained, and it is obvious that for equal slopes it is possible to compare the relative sizes of the various forms of cross-section which will give the desired capacity. It is useful to compare these relative forms with, say, a standard circular section of unit radius on the assumption that the slopes are equal, and the same type of expression is used in calculating both the average velocity and the capacity.

Assuming the standard circular section to have a radius equal to unity, the hydraulic mean radii of all types of cross-section may be expressed in the following manner :—

$$M = ER$$

where M denotes the hydraulic mean radius,
R „ radius of a standard circular section and is equal to unity,
and E is a constant for the cross-section in question.

It follows from this that the average velocity for any section may be expressed in the following manner :—

$$V = (ER)^x$$

The cross-sectional area of any particular form may also be expressed in the following manner :—

$$A = BR^2$$

where A denotes the area of cross-section,
and B is a constant.

Having expressed the velocity and area in terms of the radius of a standard circular section, it is possible to express the discharge as

$$Q = BE^x R^{(2+x)}$$

where Q denotes the capacity.

It is thus possible to express the properties of any form of cross-section in the following manner :—

(1) The area in terms of the radius of the standard circular section squared.
(2) The wetted perimeter in terms of the radius of the standard circular section.
(3) The hydraulic mean depth in terms of the radius of the standard circular section.
(4) The velocity in terms of the radius of the standard circular section raised to the power x.
(5) The discharge in terms of the radius of the standard circular section raised to the power $(2 + x)$.

Having obtained in this manner the various properties of each form of cross-section, it is possible to make the following comparisons :—

(*a*) *Comparative Capacities for Equal Diameters.*

The comparison of capacities for equal diameters is obtained directly from the discharges of each particular form of cross-section, which are expressed in terms of the unit radius raised to the power $(2 + x)$.

(*b*) *Comparative Diameters for Equal Capacities.*

In order to compare the relative diameters of each type which will give the same discharge for equal gradients, using the same form of expression when calculating the velocity and capacity, it is necessary to use the following method :—

Let $K = BE^x$ be a constant which is the coefficient of discharge of a circular section.

Let R denote the radius of a standard circular section and be equal to unity.

Let $K_1 = B_1 E_1{}^x$ be a constant which is the coefficient of discharge applicable to the form of section to be considered.

Let R_1 denote the equivalent radius of the form of section under consideration.

Then, equating the discharges,

$$K_1R_1^{(2+x)} = KR^{(2+x)},$$

whence

$$R_1 = \left(\frac{K}{K_1}\right)^{\left(\frac{1}{2+x}\right)}.$$

In this manner it is possible to express in terms of the radius of a standard circular section (that is, in terms of unity) the radius of any particular form of cross-section having the same discharge.

(*c*) *Comparative Invert-Velocities and Comparative Depths of Flow for Equal Capacities of Small Flows.*

From the various radii obtained in this manner, it is now possible to calculate constants which, when applied to the various properties of the section originally calculated at unit radius, will give those properties in terms of sections having equal capacities instead of equal diameters. These new properties may be calculated in the following manner :—

(i) The area of cross-section may be expressed in terms of unit radius squared, multiplied by the equivalent radius squared.

That is,

$$R_1^2 = \left(\frac{BE^x}{B_1E_1^x}\right)^{\left(\frac{2}{2+x}\right)},$$

and

$$A_1 = AR_1^2.$$

(ii) The wetted perimeter may be expressed in terms of unit radius, multiplied by the equivalent radius.

That is,

$$R_1 = \left(\frac{BE^x}{B_1E_1^x}\right)^{\left(\frac{1}{2+x}\right)}.$$

and

$$P_1 = PR_1,$$

where P denotes the wetted perimeter for a section of unit radius expressed in terms of the unit radius.

and P_1 ,, wetted perimeter for a section of equivalent radius expressed in terms of the unit radius.

(iii) The hydraulic mean depth may be expressed in terms of unit radius multiplied by the equivalent radius.

That is,

$$M_1 = MR_1.$$

(iv) The average velocity may be expressed in terms of the unit radius raised to the power x, multiplied by the equivalent radius raised to the power x.

That is, $$R_1^x = \left(\frac{BE^x}{B_1E_1^x}\right)^{\left(\frac{x}{2+x}\right)},$$

and $$V_1 = VR_1^x.$$

(v) The discharge may be expressed in terms of the unit radius raised to the power $(2 + x)$, multiplied by the equivalent radius raised to the power $(2 + x)$.

That is, $$R_1^{(2+x)} = \left(\frac{BE^x}{B_1E_1^x}\right).$$

But $$Q_1 = QR_1^{(2+x)},$$

and hence $$Q_1 = Q\left(\frac{K}{K_1}\right).$$

From this it will be seen that the two discharges bear the same relation to one another as the two coefficients of discharge, and that it is possible to compare both the invert-velocities for equal small-percentage capacities, and the depths of flow applicable to them.

Sewer-Sections Considered.

The sections which it is proposed to consider are as follows :—

(1) Standard circular section of unit radius.

(2) Egg-shaped section, height $2R$, width $1\frac{1}{2}R$. (It should be noted that this is the old form of egg-shaped section.)

(3) U-shaped section, form No. 1, height $2R$, width $2R$. (This section has a semicircular invert, vertical side walls and a flat top.)

(4) U-shaped section, form No. 2, height $2R$, width $2R$. (The invert in this case is perfectly flat for a width of about $0{\cdot}8R$, with a two-centred curve running from the invert to the vertical side walls, which are of height R.)

(5) U-shaped section, form No. 3, height $2R$, width $2R$. (This section has a five-centred curve for the invert, and vertical side walls $1R$ in height, and is sharply curved in the bottom of the invert.)

(6) U-shaped section, form No. 1, height $2{\cdot}33R$, width $2R$. (In this case the height of the vertical side walls is $1{\cdot}33R$, but otherwise it is the same as type No. 3.)

(7) U-shaped section, form No. 2, height $2{\cdot}33R$, width $2R$. (This is the same modification of the previous form No. 2 as type No. 6 is of type No. 3.)

(8) U-shaped section, form No. 3, height $2{\cdot}33R$, width $2R$. (The height of the vertical side walls is $1{\cdot}33R$, and this is the same modification of type No. 5 as types Nos. 6 and 7 were of types Nos. 3 and 4.)

Before considering these eight types of section, it is interesting to compare the standard circular section with type No. 3; that is,

with the U-shaped section, form No. 1, having a height and width of $2R$ and a semicircular invert.

It is a well-known fact that the hydraulic mean radius of a circular section is equal to 0·5 of the radius of that section, and if a comparison is made between a circular section and the U-shaped section of unit radius of form No. 1, it is found that the hydraulic mean radius is also 0·5 R, where R denotes the radius of the circle which can be inscribed within this particular U-shaped form of section. It follows from this that when comparing these two particular sections, each having unit radius, the velocities in each case will be equal for the same invert-gradient. It follows also that the discharges of these two particular sections will be directly proportional to their cross-sectional areas, and since the area of the circular section is 3·142 R^2, and the area of the U-shaped section of form No. 1 is 3·571 R^2, it is obvious that, for the same diameters, the capacity of the U-shaped section is 13·80 per cent. greater than the capacity of the circular section. The use of this form of section instead of the ordinary circular section having the same radius enables a reduction in size to be made.

Formula for Calculation of Sewer-Diameter.

The most generally accepted formula that is used in calculating the diameters of sewers is Santo Crimp's and Bruges' formula,[1] which was used in compiling the Tables they published in 1897, and which is as follows :—

$$V = 124M^{0\cdot67}\,S^{0\cdot50},$$
$$Q = 38\cdot63D^{2\cdot67}\,S^{0\cdot50}.$$

The formula quoted by Mr. A. A. Barnes [2] is as follows :—

$$V = 107M^{0\cdot7}\,S^{0\cdot5}$$
$$Q = 31\cdot85D^{2\cdot7}\,S^{0\cdot5}$$

where V denotes the velocity,
M ,, hydraulic mean depth,
S ,, slope or inclination,
Q ,, capacity,
and D ,, diameter.

In comparing the properties of the various sections which will be referred to later, the Santo Crimp and Bruges formula has been used.

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[1] W. E. Bruges, "Crimp and Bruges Tables and Diagrams for use in Designing Sewers and Water Mains," p. 13. London, 1936.

[2] "Hydraulic Flow Reviewed," Plates VII and VIII. London, 1916.

The constants in the above expressions, both for velocity and discharge, have no bearing on the relative merits of the sections under consideration, as they only affect the actual scale or size of the section used, and do not affect in any way the relative properties of each type of section.

Since the slopes in both formulas are raised to the power 0·50, and all the various comparisons are made on the basis of equal slopes, the use of either formula does not affect the comparisons made between the various sections. It must be noted, however, that the powers to which the hydraulic mean depths and the diameters are raised do affect these comparisons. The actual effect on the relative sizes of each particular section is, however, a small one, and since the Santo Crimp and Bruges formula is the one most generally used when considering sewer-sections, it is proposed to make the comparisons on that basis.

Comparative Discharges of Various Types of Sewers.

The properties of the various types of sewers when of equal diameter are shown in Tables I to V (pp. 280 *et seq*), which set out at various proportional depths the area, wetted perimeter, hydraulic mean depth, velocity and discharge in terms of the radius of a standard circular section.

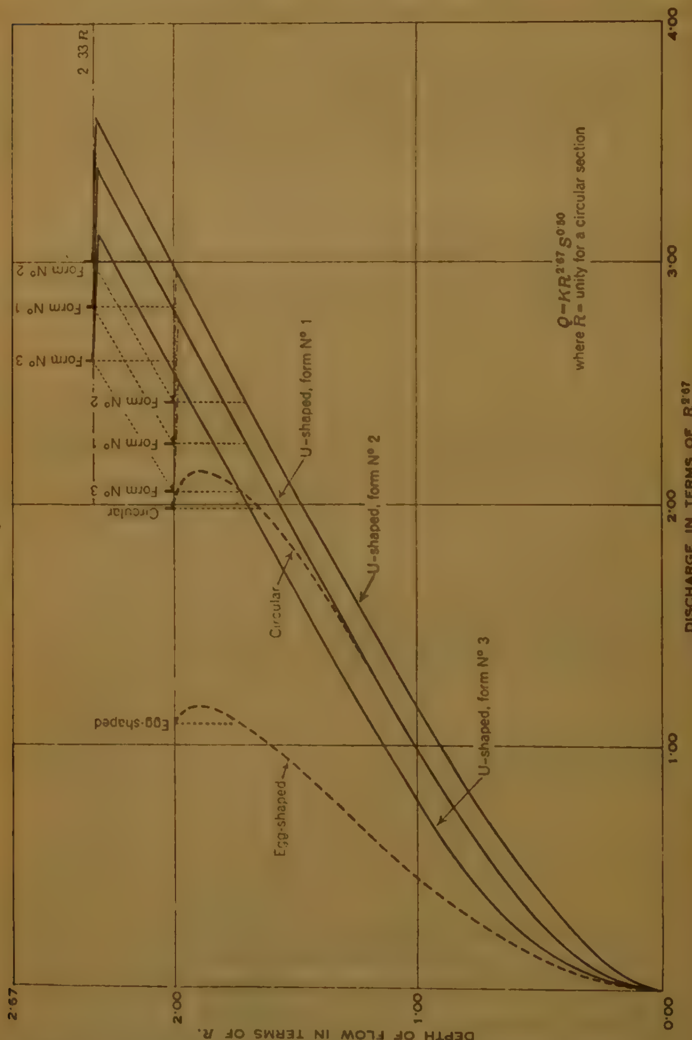
The comparative discharges of the various types of sewers, when of equal diameter, are as follows :—

(1)	Circular	$1{\cdot}979\,R^{2\cdot67}$
(2)	Egg-shaped (old form)	$1{\cdot}082\,R^{2\cdot67}$
(3)	U-shaped, form No. 1	$2{\cdot}240\,R^{2\cdot67}$
(4)	,, ,, No. 2	$2{\cdot}422\,R^{2\cdot67}$
(5)	,, ,, No. 3	$2{\cdot}052\,R^{2\cdot67}$
(6)	,, ,, No. 1	$2{\cdot}819\,R^{2\cdot67}$
(7)	,, ,, No. 2	$3{\cdot}000\,R^{2\cdot67}$
(8)	,, ,, No. 3	$2{\cdot}595\,R^{2\cdot67}$

Fig. 1 (p. 268) shows the capacities of the eight forms of section plotted in terms of the radius of the standard circular section. It should be noted that the discharges are expressed in terms of the unit radius of circular section raised to the power 2·67, and it will be seen that the U-shaped section, form No. 2, gives the largest capacity and the egg-shaped section the smallest capacity, for depths which are equal to the vertical diameter of the circular section. When the depths are increased to 2·33 R, U-shaped section, form No. 2, gives the largest capacity and the U-shaped section, form No. 3, the least capacity, for that particular depth of flow.

Fig. 1 also indicates the capacity in excess of that for a circular sewer when flowing full of which each particular type is capable,

Fig 1.



—SEWERS OF EQUAL DIAMETER: COMPARATIVE DISCHARGES.

and it will be seen that the U-shaped forms give a much larger margin in this respect than the ordinary circular section, and that the egg-shaped section gives the least margin of all.

Dimensions of Various Types of Sewers for Equal Capacities.

The comparative dimensions of the various types of sewers when of equal capacity are as follows, expressed in terms of the unit radius of a standard circular section :—

(1) Circular section, height $2R$, width $2R$.
(2) Egg-shaped section, height $2{\cdot}51\ R$, width $1{\cdot}67\ R$.
(3) U-shaped section of form No. 1, height $1{\cdot}906\ R$, width $1{\cdot}906\ R$.
(4) ,, ,, ,, No. 2, height $1{\cdot}854\ R$, width $1{\cdot}854\ R$.
(5) ,, ,, ,, No. 3, height $1{\cdot}990\ R$, width $1{\cdot}990\ R$.
(6) ,, ,, ,, No. 1, height $2{\cdot}044\ R$, width $1{\cdot}752\ R$.
(7) ,, ,, ,, No. 2, height $1{\cdot}995\ R$, width $1{\cdot}710\ R$.
(8) ,, ,, ,, No. 3, height $2{\cdot}107\ R$, width $1{\cdot}806\ R$.

The method of calculation used to obtain the comparative dimensions shown above is set out in Tables VI to VIII (pp. 282–3). Table VI shows in summarized form the comparative discharges of the various sections for equal diameters.

The values of the equivalent radius R_1 together with the constants required to calculate the properties of each section for equal discharges are shown on Table VII, and Table VIII sets out in summarized form the comparative areas, velocities, etc., for equal discharges, in terms of unit radius of the standard circular section.

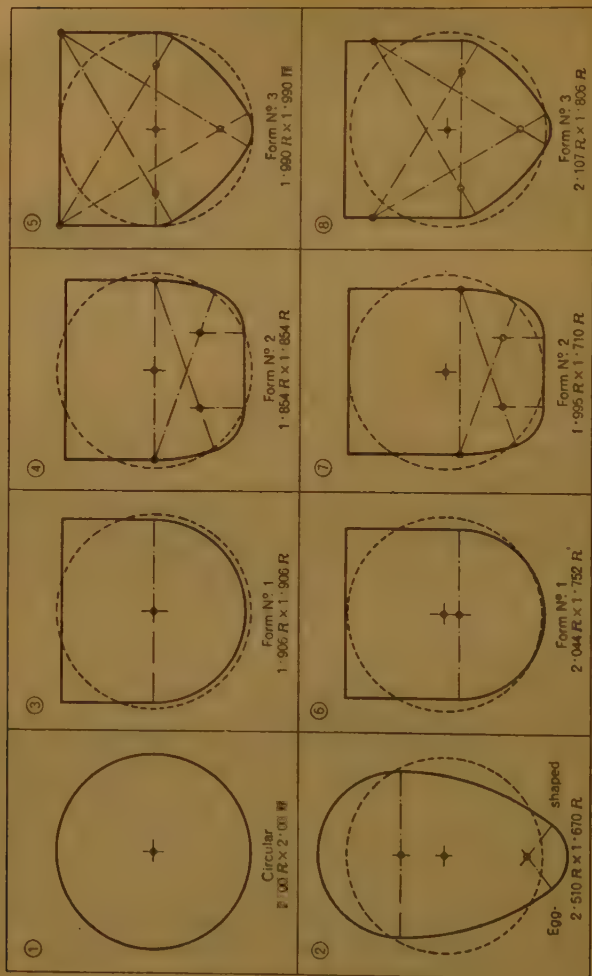
The comparative dimensions of these eight forms of section are shown in *Figs. 2* (p. 270), and in each case a standard circular section of unit radius has been superimposed in order to aid comparison. It will be seen that in each type there is a considerable reduction in overall width with the exception of type No. 5, where the difference is negligible. The greatest reduction in width applies to the egg-shaped section, which at the same time has the greatest height.

Each of these particular equivalent sections gives the same capacity for the same gradient, and the choice of any one of them depends in the first instance on the peculiar circumstances of the situation for which the sewer is required, and, where the circumstances are identical, upon the relative cost.

Invert-Velocities for Small Discharges.

The consideration of the invert-velocities which are obtained with a particular form of sewer cross-section is most important, particularly when the sewer is part of a combined system carrying heavy storm-discharges and comparatively small dry-weather flows. In the case of most trunk sewers which form part of a combined system, the dry-weather flow represents something in the neighbourhood of 1 per cent. of the total discharge, and it is useful to make a

Figs. 2.



R = unity for a circular cross-section

SEWERS OF EQUAL CAPACITY: COMPARATIVE DIMENSIONS.

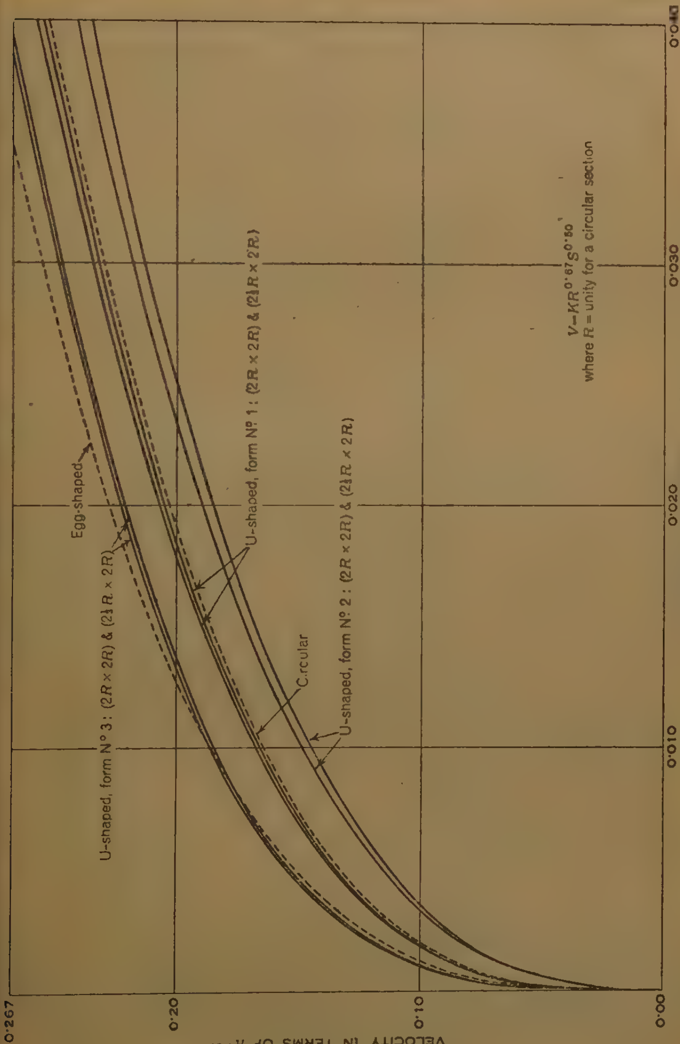
comparison between the average velocities applicable to small flows.

The relative values of the velocities at 1 per cent. of the total discharge in the sections under consideration are as follows:—

(1)	Circular	$0{\cdot}202\ R^{0{\cdot}67}$
(2)	Egg-shaped	$0{\cdot}228\ R^{0{\cdot}67}$
(3)	U-shaped section, form No. 1	$0{\cdot}205\ R^{0{\cdot}67}$
(4)	,, ,, ,, No. 2	$0{\cdot}184\ R^{0{\cdot}67}$
(5)	,, ,, ,, No. 3	$0{\cdot}221\ R^{0{\cdot}67}$
(6)	,, ,, ,, No. 1	$0{\cdot}207\ R^{0{\cdot}67}$
(7)	,, ,, ,, No. 2	$0{\cdot}189\ R^{0{\cdot}67}$
(8)	,, ,, ,, No. 3	$0{\cdot}223\ R^{0{\cdot}67}$

The comparative velocities of the various forms of cross-section of equal capacity are shown in *Fig. 3*, from which it is apparent that the egg-shaped section gives the best self-cleansing velocity, and that

Fig. 3.



SEWERS OF EQUAL CAPACITY : COMPARATIVE VELOCITIES.

form No. 3 lies very close to it, the difference being approximately 3 per cent. U-shaped sections of form No. 1 give slightly greater velocities than the ordinary standard circular section. These sections, however, give approximately 90 per cent. of the velocity

obtained by the use of a U-shaped section. U-shaped sections of form No. 2 lie close to each other, and give a velocity which is approximately 82 per cent. of the velocity obtainable from an egg-shaped section.

From this it is apparent that the use of U-shaped sections of forms Nos. 1 and 3 will give invert-velocities which lie between those obtainable from egg-shaped and from circular sections, and that the advantage gained in using the egg-shaped section rather than a circular section is not considerable from the point of view of self-cleansing velocities.

The adoption of U-shaped sections of form No. 2, although giving smaller velocities than the circular section, would apparently be quite applicable to sewers where the percentage of dry-weather flow is greater than 1 per cent., or where the invert-gradient is sufficient to obtain a self-cleansing velocity.

Depth of Flow for Small Discharges.

In addition to considering velocities when dealing with small discharges, it is also necessary to consider the depths of flow given by these small discharges for the various forms of sewer.

From the properties of the various sections obtained in the first instance, and the use of the various constants which reduce their diameter to sewers of equal capacity, it is possible to indicate the relative depths of flow obtained in each case for small-percentage discharges. *Fig. 4* shows the depths of flow applicable to each form of cross-section of equal capacity, from which it will be seen that the depths of flow at 1 per cent. of the total discharge are as follows:—

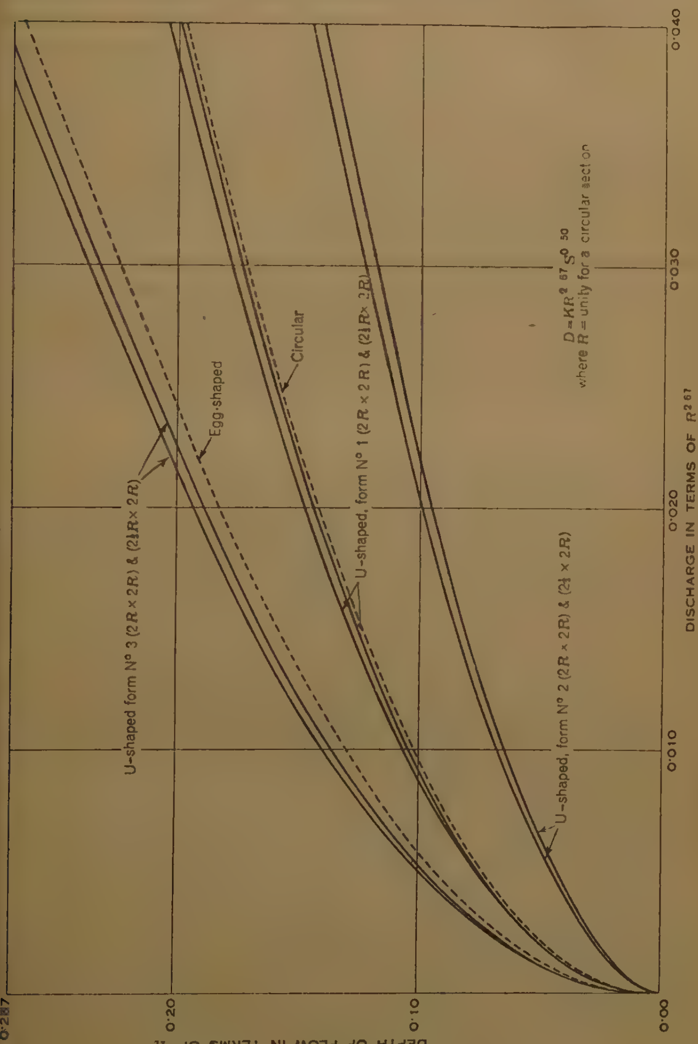
(1)	Circular	0·142 *R*.
(2)	Egg-shaped	0·182 *R*.
(3)	U-shaped, form No. 1	0·144 *R*.
(4)	„ „ No. 2	0·096 *R*.
(5)	„ „ No. 3	0·188 *R*.
(6)	„ „ No. 1	0·148 *R*.
(7)	„ „ No. 2	0·098 *R*.
(8)	„ „ No. 3	0·193 *R*.

It will be seen that the U-shaped sections of form No. 3 give greater depths of flow than the egg-shaped section, and U-shaped sections of form No. 1 give a greater depth than a circular section. U-shaped sections of form No. 2 give the least depth of flow.

It must be remembered that the actual size of the sewer has a direct bearing in this instance on the depths of flow obtainable, and since the types of sewer under consideration are of relatively large dimensions, this particular aspect of the problem is not so important as the question of self-cleansing velocities. Sections of form No. 2,

however, should only be used after carefully considering whether the depth of flow obtainable during small discharges is sufficient to transport properly the solid matter in the sewage. U-shaped sections

Fig. 4.



Sewers of Equal Capacity: Comparative Depth of Flow.

of form No. 1 can be used with perfect safety in cases where a circular section would give a sufficient depth of flow, and U-shaped sections of form No. 3 will give a better depth of flow than the ordinary egg-shaped section.

The adoption of U-shaped sections of form No. 1 gives, for all practical purposes, the invert-velocities and depths of flow which follow from the use of circular sections, with the advantage of increased capacity for the same leading diameters, and reduction in sizes for the same capacities. The adoption of U-shaped sections of form No. 2 result in invert-velocities which are some 10 per cent. less than the invert-velocities obtainable from circular sections, which with reasonable gradients is no great disadvantage from a practical standpoint.

Sections of form No. 2, however, show a considerable reduction in depths of flow for small discharges, and it would seem that they should not be adopted without careful consideration of this aspect of the circumstances for which the sewer is to be constructed. They offer, however, considerable advantages so far as capacity is concerned, and show a considerable reduction in size for sewers of the same capacity.

U-shaped sections of form No. 3 offer the same advantages as egg-shaped sections with regard to invert-velocities and depths of flow for small discharges, but show no greater reduction in diameter, when compared with circular sections.

The graphs shown in *Figs. 3* and *4* were plotted from the information given in Tables IX to XV (pp. 284 *et seq.*) inclusive, these figures being obtained from the original properties of the various sections shown in Tables I to V, multiplied by the various constants obtained from the equivalent radius R_1, and shown in Table VII.

Relative Costs of Various Sewer-Sections.

In order to consider the relative cost of the various forms of cross-section, it is necessary, first of all, to consider the best type of construction which should be adopted for the class of work under consideration. It is not proposed to compare costs on any other basis than that which is applicable to the best type of construction, to be adopted for trunk sewers in urban areas.

It is usual, in many instances, to construct sewers of reinforced-concrete tubes, surrounded with concrete, but as this form of construction is only economical for sewers which are smaller than 42 inches in diameter, it is proposed to consider the relative costs of sewers 42 inches in diameter and over, where the use of a 4½-inch brick ring surrounded with concrete is the most economical proposition.

The various comparisons for sewers in trench are made on the basis of circular sewers ranging in diameter from 42 to 66 inches, constructed with a 4½-inch ring of double-pressed engineering brickwork,

set in cement and surrounded with concrete, the thickness of the concrete below the invert being 9 inches and on either side $7\frac{1}{2}$ inches, with a minimum cover of 6 inches at the top and 6 inches on the 45-degree splay at either side of the top. For the equivalent diameters of egg-shaped sewers in trench the form of construction is a $4\frac{1}{2}$-inch ring of brickwork with the same thickness of concrete surround. For the various U-shaped sections in trench, the comparison is made on the basis of a $4\frac{1}{2}$-inch ring of brickwork as before, with the insertion of a header-course immediately under the flat top and at the springing-line, the thickness of concrete being 9 inches in the invert and 9 inches at either side. The flat roofs of the U-shaped sections are constructed in the form of pre-cast units, about 18 inches in length and of a sufficient thickness to carry the weight of the earth filling placed upon them.

For sewers which are to be constructed in tunnel no difference is made in the form of construction so far as brickwork and pre-cast concrete slabs are concerned, but the various thicknesses of concrete provided for are as follows :—

For circular and egg-shaped sewers :

A 9-inch thickness of concrete in the invert and at the sides, with a 12-inch thickness at the crown.

For U-shaped sewers :

A 9-inch thickness of concrete at the invert and the sides, with a 15-inch thickness at the crown.

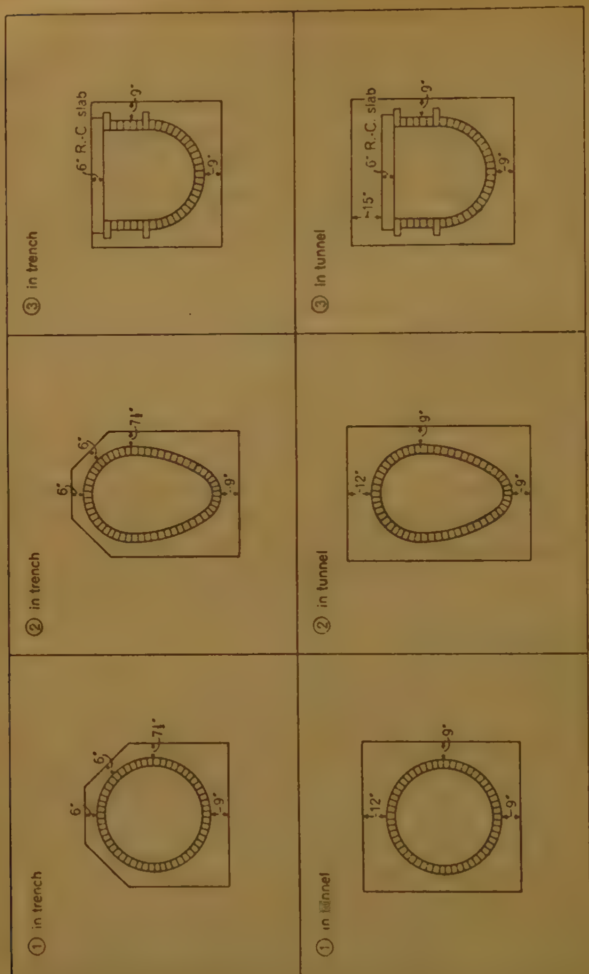
Figs. 5 (p. 276) show circular, egg-shaped and U-shaped sewers of form No. 1 for an equivalent circular diameter of 48 inches, both in trench and in tunnel, showing provision for an extra $1\frac{1}{2}$ inch of concrete on the sides for U-shaped sections in trench, and for an additional thickness of 3 inches at the crown for U-shaped sections in tunnel.

The additional thickness provided for in trench is considered necessary because of the absence of arching effect present in both circular and egg-shaped sections, although it is more than probable that a total thickness of 12 inches of concrete and brickwork would be sufficient. The 15-inch thickness of concrete over the pre-cast slabs is provided in order to ensure that sufficient room is given to pack the headings in a proper manner.

In calculating the quantities of excavation per linear yard of sewer, the depths have been taken in each case to the crown of the section, as it is the crown-gradient and not the invert-gradient which decides the capacity of a sewer and provides the datum from which a basis of comparison can be made.

The unit prices of excavation, brickwork, concrete, and reinforced-

Figs. 5.



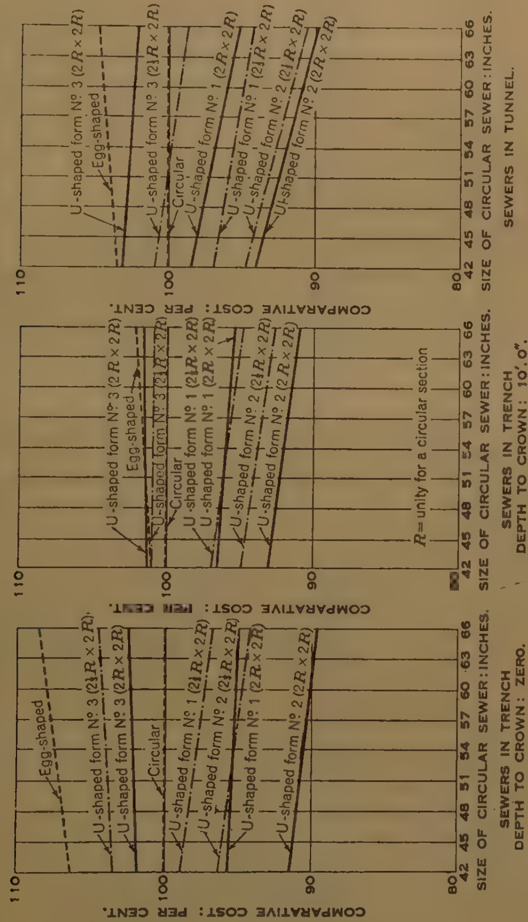
CONSTRUCTION OF SEWERS OF EQUAL CAPACITY.

concrete slabs upon which the relative prices have been calculated are as follows:—

	In trench: per cubic yard.	In tunnel: per cubic yard.
Excavation	10/-	20/-
Brickwork	80/-	80/-
Concrete	35/-	40/-
Reinforced-concrete slabs	70/-	70/-

Figs. 6 show the relative costs of the eight types of sewer for sewers in trench where the depth to crown is zero, for sewers in trench where the depth to crown is 10 feet, and for sewers in tunnel. In each case

Figs. 6.



COMPARATIVE COSTS OF SEWERS.

the sizes range from 42 inches to 66 inches diameter of standard circular section, and the cost of the circular section is expressed as 100.

For sewers of zero depth to crown, the relative values are approximately as follows :—

(1)	Circular	A constant value of 100.
(2)	Egg-shaped	An increase of from 6½ to 8 per cent.
(3)	U-shaped section, form No. 1 .	A reduction of from 4 to 6 per cent.
(4)	,, ,, ,, No. 2 .	A reduction of from 8 to 10 per cent.
(5)	,, ,, ,, No. 3 .	An increase of from 1 to 2½ per cent.
(6)	,, ,, ,, No. 1 .	A reduction of from 1 to 3½ per cent.
(7)	,, ,, ,, No. 2 .	A reduction of from 3 to 5½ per cent.
(8)	,, ,, ,, No. 3 .	An increase of from 2½ to 4 per cent.

For sewers in trench where the depth to crown is 10 feet the relative costs are as follows :—

(1)	Circular	A constant value of 100.
(2)	Egg-shaped	An increase of from 1 to 2 per cent.
(3)	U-shaped section, form No. 1 .	A decrease of from 3½ to 5 per cent.
(4)	,, ,, ,, No. 2 .	A decrease of from 7 to 9 per cent.
(5)	,, ,, ,, No. 3 .	An increase of from 1 to 1½ per cent.
(6)	,, ,, ,, No. 1 .	A decrease of from 3 to 5 per cent.
(7)	,, ,, ,, No. 2 .	A decrease of from 5 to 7 per cent.
(8)	,, ,, ,, No. 3 .	An increase of 1 per cent.

For sewers in tunnel, the relative prices are as follows :—

(1)	Circular	A constant value of 100.
(2)	Egg-shaped	An increase of from 1½ to 3½ per cent.
(3)	U-shaped section, form No. 1 .	A decrease of from 2 to 5 per cent.
(4)	,, ,, ,, No. 2 .	A decrease of from 5½ to 10 per cent.
(5)	,, ,, ,, No. 3 .	An increase of from ½ to 3½ per cent.
(6)	,, ,, ,, No. 1 .	A decrease of from 3 to 6 per cent.
(7)	,, ,, ,, No. 2 .	A decrease of from 6½ to 10 per cent.
(8)	,, ,, ,, No. 3 .	An increase of from 0 to 1 per cent.

From these comparisons it is evident that for brickwork construction with concrete surround, the U-shaped sections of forms Nos. 1 and 2 are cheaper than the circular form of construction, the saving effected being about from 5 to 10 per cent., and proportions which give equal heights and widths are more economical than proportions which give a greater height than width.

Where it is necessary to obtain better invert-velocities, the increase in cost over a circular section by the adoption of either an egg-shaped section or a U-shaped section of form No. 3 will result in an increase in cost of between 1 and 8 per cent., but the application of the U-shaped section of form No. 3 will show no greater increase in cost over the egg-shaped form, with a possible saving of about 3 per cent. The diameter of the section has a direct bearing on the relative costs, and in the general case the larger the diameter the greater the saving will be, but it is doubtful whether it is economical to construct

U-shaped sections where the capacity is less than that of a 42-inch diameter circular section.

The saving to be effected by the general adoption of U-shaped sections may seem to be trifling, but the fact remains that they are cheaper than either circular or egg-shaped sections, and their adoption in large works of sewer-construction will undoubtedly effect considerable saving in capital cost.

Two U-shaped sewers of form No. 1 have been constructed in Sunderland and three more are to be commenced in the near future, involving a total length of 6,176 linear yards ranging from 30-inch by 30-inch to 66-inch by 66-inch in size. These particular sewers have been approved by the Ministry of Health, and in the case of one contract alternative tenders were obtained for circular sewers in reinforced-concrete tubes and for the U-shaped sewers in brickwork. The total value of this contract was about £62,700, of which £22,500 was for U-shaped sewers, the tender for circular sewers throughout being £66,000. The adoption of U-shaped sections in this case resulted in a saving of £3,300 in capital cost, which represents a saving of about 15 per cent.

This reduction in cost is greater than the reductions indicated in *Figs. 6*, but it must be remembered that tenders were obtained for circular concrete-tube sewers, and that in *Figs. 6* brick sewers are compared in each case.

The Paper is accompanied by six sheets of diagrams, from which the Figures in the text have been prepared, and by twenty-one sheets of Tables, from parts of which the following Tables I to XV have been compiled.

TABLE I.—CIRCULAR SEWERS.

Diameter: 2·00 *R*.
Area: 3·142 $R^{2\cdot00}$.
Wetted perimeter: 6·283 *R*.
Hydraulic mean depth: 0·500 *R*.
Discharge: 1·979 $R^{2\cdot67}$.

Proportion of depth.	Area, R^2.	Wetted perimeter, *R*.	Hydraulic mean depth, *R*.	Velocity, $R^{0\cdot67}$.	Discharge, $R^{2\cdot67}$.
0·02	0·0053	0·4003	0·0133	0·0561	0·0003
0·04	0·0151	0·5719	0·0264	0·0887	0·0014
0·06	0·0273	0·6914	0·0395	0·1158	0·0032
0·08	0·0421	0·7994	0·0524	0·1399	0·0060
0·10	0·0580	0·8980	0·0640	0·1618	0·0095
0·12	0·0769	0·9884	0·0778	0·1822	0·0141
0·14	0·0967	1·0454	0·0925	0·2012	0·0194
0·16	0·1178	1·1481	0·1026	0·2193	0·0257
0·18	0·1401	1·2193	0·1149	0·2364	0·0331
0·20	0·165	1·288	0·128	0·254	0·0414
0·30	0·296	1·589	0·186	0·326	0·096
0·40	0·448	1·853	0·242	0·389	0·174
0·60	0·776	2·281	0·340	0·487	0·378
0·80	1·171	2·733	0·428	0·568	0·665
1·00	1·571	3·142	0·500	0·630	0·989
1·20	1·971	3·550	0·555	0·675	1·331
1·40	2·366	4·002	0·591	0·704	1·665
1·60	2·694	4·430	0·608	0·718	1·934
1·80	2·977	4·995	0·596	0·708	2·108
2·00	3·142	6·283	0·500	0·630	1·979

TABLE II.—EGG-SHAPED SEWERS (OLD FORM).

Height: 2·00 *R*.
Area: 2·041 R^2.
Wetted perimeter: 5·287 *R*.
Breadth: 1·33 *R*.
Hydraulic mean depth: 0·386 *R*.
Discharge: 1·082 $R^{2\cdot67}$.

Proportion of depth.	Area, R^2.	Wetted perimeter, *R*.	Hydraulic mean depth, *R*.	Velocity, $R^{0\cdot67}$.	Discharge $R^{2\cdot67}$.
0·02	0·0030	0·2290	0·0131	0·0556	0·00017
0·04	0·0084	0·3243	0·0259	0·0875	0·00074
0·06	0·0153	0·3994	0·0383	0·1136	0·00174
0·08	0·0234	0·4652	0·0503	0·1362	0·00325
0·10	0·0324	0·5234	0·0619	0·1564	0·00519
0·12	0·0421	0·5760	0·0731	0·1748	0·00757
0·14	0·0524	0·6253	0·0838	0·1914	0·01017
0·16	0·0634	0·6744	0·0940	0·2116	0·01331
0·18	0·0749	0·7270	0·1034	0·2204	0·01666
0·20	0·0870	0·7721	0·1126	0·2331	0·02056
0·30	0·158	1·018	0·155	0·288	0·046
0·40	0·239	1·252	0·191	0·331	0·079
0·60	0·449	1·755	0·256	0·402	0·175
0·80	0·657	2·105	0·312	0·460	0·303
1·00	0·904	2·525	0·358	0·504	0·457
1·20	1·165	2·930	0·398	0·541	0·632
1·40	1·433	3·330	0·430	0·569	0·817
1·60	1·688	3·745	0·451	0·588	0·995
1·80	1·910	4·220	0·452	0·589	1·126
2·00	2·041	5·287	0·386	0·530	1·082

TABLE III.—U-SHAPED SEWERS, FORM NO. 1.

Area: 3·571 R^2. Hydraulic mean depth: 0·694 R.
Wetted perimeter: 5·142 R. Discharge: 2·799 $R^{2 \cdot 67}$

Proportion of depth.	Area, R^2.	Wetted perimeter, R.	Hydraulic mean depth, R.	Velocity, $R^{0 \cdot 67}$.	Discharge, $R^{2 \cdot 67}$.
0·50	0·613	2·092	0·292	0·440	0·270
0·60	0·776	2·281	0·340	0·487	0·378
0·80	1·171	2·733	0·428	0·568	0·665
1·00	1·571	3·142	0·500	0·630	0·989
1·20	1·971	3·542	0·556	0·677	1·334
1·40	2·371	3·942	0·601	0·712	1·688
1·60	2·771	4·342	0·638	0·741	2·053
1·80	3·171	4·742	0·669	0·765	2·426
2·00	3·571	5·142	0·694	0·784	2·799
*2·00	3·571	7·142	0·500	0·630	2·240
2·20	3·971	5·542	0·716	0·801	3·181
*2·33	4·238	7·809	0·542	0·665	2·819

* Closed top.

TABLE IV.—U-SHAPED SEWERS, FORM NO. 2.

Flat-invert type.

Area: 3·786 R^2. Hydraulic mean depth: 0·511 R.
Wetted perimeter: 7·418 R. Discharge: 2·422 $R^{2 \cdot 67}$.

Proportion of depth.	Area, R^2.	Wetted perimeter, R.	Hydraulic mean depth, R.	Velocity, $R^{0 \cdot 67}$.	Discharge, $R^{2 \cdot 67}$.
0·02	0·0204	1·11	0·0184	0·0700	0·0014
0·04	0·0434	1·23	0·0353	0·108	0·0047
0·06	0·0682	1·32	0·0516	0·138	0·0094
0·08	0·0968	1·40	0·0690	0·169	0·0164
0·10	0·1220	1·47	0·083	0·190	0·0230
0·12	0·1526	1·54	0·099	0·215	0·0328
0·14	0·1834	1·60	0·115	0·236	0·0433
0·16	0·2142	1·65	0·130	0·257	0·0550
0·18	0·2460	1·71	0·144	0·275	0·0675
0·20	0·2780	1·76	0·158	0·292	0·0810
0·30	0·446	1·988	0·224	0·369	0·164
0·40	0·682	2·202	0·310	0·458	0·311
0·60	0·997	2·614	0·382	0·527	0·526
0·80	1·387	3·018	0·460	0·597	0·828
1·00	1·786	3·418	0·523	0·649	1·160
1·20	2·186	3·818	0·573	0·690	1·506
1·40	2·586	4·218	0·613	0·722	1·865
1·60	2·986	4·618	0·647	0·748	2·230
1·80	3·386	5·018	0·675	0·769	2·600
2·00	3·786	5·418	0·698	0·787	2·978
*2·00	3·786	7·418	0·511	0·640	2·422
2·20	4·186	5·818	0·719	0·803	3·361
*2·33	4·456	8·085	0·552	0·673	3·000

* Closed top.

TABLE V.—U-SHAPED SEWERS, FORM NO. 3.
FIVE-CENTRED INVERT TYPE.

Area : 3·328 R^2. Hydraulic mean depth : 0·480 R.
Wetted perimeter : 6·950 R. Discharge : 2·050 $R^{2.67}$.

Proportion of depth.	Area, R^2.	Wetted perimeter, R.	Hydraulic mean depth, R.	Velocity, $R^{0.67}$.	Discharge, $R^{2.67}$.
0·02	0·0031	0·232	0·013	0·056	0·00017
0·04	0·0084	0·329	0·025	0·085	0·00071
0·06	0·0158	0·407	0·039	0·115	0·00182
0·08	0·0244	0·483	0·050	0·136	0·0033
0·10	0·0342	0·559	0·061	0·155	0·0054
0·12	0·045	0·634	0·071	0·172	0·0077
0·14	0·057	0·706	0·081	0·187	0·0107
0·16	0·070	0·776	0·090	0·199	0·0139
0·18	0·085	0·844	0·101	0·217	0·0184
0·20	0·100	0·909	0·110	0·229	0·0229
0·30	0·188	1·217	0·155	0·288	0·0542
0·40	0·301	1·506	0·200	0·342	0·103
0·60	0·579	2·038	0·284	0·432	0·250
0·80	0·919	2·518	0·365	0·510	0·469
1·00	1·328	2·950	0·450	0·587	0·780
1·20	1·728	3·350	0·516	0·643	1·110
1·40	2·128	3·750	0·570	0·688	1·470
1·60	2·528	4·150	0·610	0·720	1·825
1·80	2·928	4·550	0·645	0·746	2·180
2·00	3·328	4·950	0·672	0·767	2·554
*2·00	3·328	6·950	0·480	0·614	2·050
2·20	3·728	5·350	0·697	0·786	2·930
*2·33	3·995	7·617	0·524	0·650	2·595

* Closed Top.

TABLE VI.—COMPARATIVE DISCHARGES FOR EQUAL DIAMETERS AND GRADIENTS.

Properties of sections flowing full.

Reference No.	Section.	Area, R^2.	Wetted perimeter, R.	Hydraulic mean depth, R.	Velocity, $R^{0.67}$.	Discharge $R^{2.67}$.
		B	B/E	E	$E^{0.67}$.	$BE^{0.67}$.
1	Circular . .	3·142	6·283	0·500	0·630	1·979
2	Egg-shaped . (old form).	2·041	5·287	0·386	0·530	1·082
	U-shaped. 2·00 $R \times$ 2·00 R					
3	Form No. 1 .	3·571	7·142	0·500	0·630	2·240
4	Form No. 2 .	3·786	7·418	0·511	0·640	2·422
5	Form No. 3 .	3·328	6·950	0·480	0·614	2·052
	U-shaped 2·33 $R \times$ 2·00 R					
6	Form No. 1 .	4·238	7·809	0·542	0·665	2·819
7	Form No. 2 .	4·456	8·085	0·552	0·673	3·000
8	Form No. 3 .	3·995	7·617	0·524	0·650	2·595

TABLE VII.—COMPARATIVE RADII FOR EQUAL DISCHARGES.

Reference No.	Section.	$\frac{1 \cdot 979}{K_1}$	R_1	R_1^2	$R_1^{0 \cdot 67}$.	$R_1^{2 \cdot 67}$.
1	Circular . .	1·000	1·000	1·000	1·000	1·000
2	Egg-shaped . (old form)	1·829	1·255	1·575	1·163	1·832
	U-shaped $2 \cdot 00\ R \times 2 \cdot 00\ R$					
3	Form No. 1 .	0·880	0·953	0·910	0·968	0·880
4	" No. 2 .	0·817	0·927	0·859	0·951	0·817
5	" No. 3 .	0·986	0·995	0·990	0·996	0·986
	U-shaped $2 \cdot 33\ R \times 2 \cdot 00\ R$					
6	Form No. 1 .	0·702	0·876	0·767	0·915	0·702
7	" No. 2 .	0·659	0·855	0·732	0·901	0·659
8	" No. 3 .	0·763	0·903	0·815	0·933	0·763

TABLE VIII.—COMPARATIVE AREAS, VELOCITIES, ETC., FOR EQUAL DISCHARGES IN TERMS OF UNIT RADIUS FOR STANDARD CIRCULAR SECTIONS.

Reference No.	Section.	Area, R^2.	Wetted perimeter, R.	Hydraulic mean depth, R.	Velocity, $R^{0 \cdot 67}$.	Discharge, $R^{2 \cdot 67}$.
1	Circular . .	3·142	6·283	0·500	0·630	1·979
2	Egg-shaped . (old form)	3·214	6·635	0·484	0·617	1·983
	U-shaped $2 \cdot 00\ R \times 2 \cdot 00\ R$					
3	Form No. 1 .	3·242	6·806	0·476	0·608	1·974
4	" No. 2 .	3·252	6·876	0·473	0·607	1·974
5	" No. 3 .	3·295	6·920	0·478	0·612	1·980
	U-shaped $2 \cdot 33\ R \times 2 \cdot 00\ R$					
6	Form No. 1 .	3·250	6·840	0·475	0·608	1·979
7	" No. 2 .	3·262	6·910	0·472	0·606	1·979
8	" No. 3 .	3·255	6·987	0·473	0·607	1·980

TABLE IX.—EGG-SHAPED SEWERS (OLD FORM).

Height: 2·51 *R*. Breadth: 1·67 *R*.
Equivalent in capacity to standard circular section of unit radius.

Depth, R.	Area, R^2.	Hydraulic mean depth, R.	Velocity, $R^{0\cdot67}$.	Discharge, $R^{2\cdot67}$.
0·0251	0·0047	0·0164	0·0645	0·00031
0·0502	0·0132	0·0325	0·1015	0·00135
0·0753	0·0241	0·0480	0·1318	0·00318
0·1004	0·0368	0·0631	0·1580	0·00582
0·1255	0·0510	0·0777	0·1814	0·00925
0·1506	0·0663	0·0917	0·2037	0·01352
0·1757	0·0825	0·1052	0·2220	0·01832
0·2008	0·0998	0·1179	0·2454	0·02449
0·2259	0·1179	0·1297	0·2556	0·03060
0·2510	0·1370	0·1413	0·2704	0·03708

TABLE X.—U-SHAPED SEWERS, FORM NO. 1.

Height: 1·906 *R*. Breadth: 1·906 *R*.
Equivalent in capacity to standard circular section of unit radius.

Depth, R.	Area, R^2.	Hydraulic mean depth, R.	Velocity, $R^{0\cdot67}$.	Discharge, $R^{2\cdot67}$
0·0191	0·0048	0·0127	0·0543	0·00026
0·0381	0·0137	0·0252	0·0859	0·00118
0·0572	0·0248	0·0376	0·1123	0·00279
0·0762	0·0382	0·0500	0·1355	0·00518
0·0953	0·0527	0·0610	0·1569	0·00826
0·1144	0·0701	0·0742	0·1765	0·01270
0·1334	0·0878	0·0882	0·1952	0·01715
0·1525	0·1072	0·0978	0·2123	0·02276
0·1715	0·1273	0·1095	0·2292	0·02915
0·1906	0·1501	0·1222	0·2462	0·03695

TABLE XI.—U-SHAPED SEWERS, FORM NO. 2.

Height: 1·854 *R*. Breadth: 1·854 *R*.
Equivalent in capacity to standard circular section of unit radius.

Depth, R.	Area, R^2.	Hydraulic mean depth, R.	Velocity, $R^{0\cdot67}$.	Discharge, $R^{2\cdot67}$
0·0185	0·0175	0·0171	0·0666	0·00116
0·0371	0·0373	0·0327	0·1027	0·00383
0·0556	0·0586	0·0478	0·1312	0·00769
0·07416	0·0831	0·0640	0·1607	0·01335
0·0927	0·1048	0·0769	0·1807	0·01894
0·1112	0·1311	0·0918	0·2045	0·02681
0·1298	0·1575	0·1066	0·2244	0·03534
0·1483	0·1840	0·1205	0·2444	0·04497
0·1669	0·2113	0·1335	0·2615	0·05526
0·1854	0·2388	0·1465	0·2777	0·06632

Table XII.—U-Shaped Sewers (Closed Top), Form No. 3.

Height : 1·990 *R*. Breadth : 1·990 *R*.

Equivalent in capacity to standard circular section of unit radius.

Depth, *R*.	Area, R^2.	Hydraulic mean depth, *R*.	Velocity, $R^{0.67}$.	Discharge, $R^{2.67}$.
0·0199	0·0031	0·0129	0·0558	0·00017
0·0398	0·0083	0·0249	0·0846	0·00070
0·0597	0·0156	0·0388	0·1145	0·00179
0·0796	0·0242	0·0497	0·1355	0·00325
0·0995	0·0338	0·0607	0·1542	0·00532
0·1194	0·0445	0·0707	0·1711	0·00760
0·1393	0·0564	0·0806	0·1860	0·01055
0·1593	0·0693	0·0895	0·1780	0·01370
0·1792	0·0841	0·1005	0·2160	0·01815
0·1990	0·0990	0·1090	0·2280	0·02260

Table XIII.—U-Shaped Sewers (Closed Top), Form No. 1.

Height : 2·044 *R*. Breadth : 1·752 *R*.

Equivalent in capacity to standard circular section of unit radius.

Depth, *R*.	Area, R^2.	Hydraulic mean depth, *R*.	Velocity, $R^{0.67}$.	Discharge, $R^{2.67}$.
0·0175	0·0041	0·0116	0·0513	0·00021
0·0350	0·0116	0·0231	0·0812	0·00098
0·0526	0·0209	0·0346	0·1060	0·00225
0·0701	0·0323	0·0459	0·1280	0·00421
0·0876	0·0445	0·0561	0·1480	0·00669
0·1051	0·0590	0·0681	0·1667	0·00990
0·1226	0·0742	0·0810	0·1841	0·01362
0·1202	0·0904	0·0899	0·2006	0·01804
0·1577	0·1074	0·1006	0·2163	0·02324
0·1752	0·1265	0·1121	0·2324	0·02906

Table XIV.—U-Shaped Sewers (Closed Top), Form No. 2.

Height : 1·995 *R*. Breadth : 1·710 *R*.

Equivalent in capacity to standard circular section of unit radius.

Depth, *R*.	Area, R^2.	Hydraulic mean depth, *R*.	Velocity, $R^{0.67}$.	Discharge, $R^{2.67}$.
0·0171	0·0149	0·0157	0·0631	0·00092
0·0342	0·0318	0·0302	0·0973	0·00310
0·0513	0·0499	0·0441	0·1243	0·00619
0·0684	0·0709	0·0590	0·1523	0·01081
0·0855	0·0893	0·0710	0·1712	0·01516
0·1026	0·1117	0·0847	0·1937	0·02162
0·1197	0·1342	0·0983	0·2126	0 02854
0·1368	0·1568	0·1150	0·2316	0·03625
0·1539	0·1801	0·1274	0·2478	0·04448
0·1710	0·2035	0·1398	0·2631	0·05338

TABLE XV.—U-SHAPED SEWERS (CLOSED TOP), FORM NO. 3.

Height: 2·107 *R*. Breadth: 1·806 *R*.

Equivalent in capacity to standard circular section of unit radius.

Depth, *R*.	Area, R^2.	Hydraulic mean depth, *R*.	Velocity, $R^{0\cdot 67}$.	Discharge, $R^{2\cdot 67}$.
0·0181	0·0025	0·0117	0·0522	0·00013
0·0365	0·0068	0·0226	0·0793	0·00054
0·0542	0·0129	0·0352	0·1072	0·00139
0·0723	0·0199	0·0452	0·1270	0·00252
0·0903	0·0279	0·0550	0·1445	0·00412
0·1085	0·0367	0·0641	0·1605	0·00587
0·1263	0·0465	0·0731	0·1745	0·00816
0·1445	0·0571	0·0812	0·1860	0·01060
0·1625	0·0692	0·0914	0·2020	0·01405
0·1806	0·0815	0·0995	0·2140	0·01745

Paper No. 5082.

"The Flow of Water in Short Channels."

By CHARLES FREDERICK JASON LISLE, B.Sc., Assoc. M. Inst. C.E

(*Ordered by the Council to be published with written discussion.*) [1]

TABLE OF CONTENTS.

INTRODUCTION.

THE simplest, most ancient, and probably the most economical method of transporting water from one point to another is to pass it through an open channel, employing the force of gravity as the motive power. Through the diligent and careful observations and mathematical analyses made by past and present scientists, Tables, formulas and graphs are available, giving the quantity and depth of water that will flow in a channel of any constant cross-section at almost any gradient, and with almost any type of surface. These formulas have, however, one common limitation, and that is that the water enters and leaves the channel at such a depth that a uniform velocity is maintained throughout its length. In short channels these conditions are rarely experienced in practice, and the need for a formula to determine the contour of the water-surface in a channel which is not long enough to establish a uniform velocity has been realized by Mr. H. E. Babbit, in 1922, and by Mr. B. A.

[1] Correspondence on this Paper can be accepted until the 15th March, 1938, and will be published in the Institution Journal for October, 1938.—ACTING SEC. INST. C.E.

Bakhmeteff. The works of the latter, in particular, form a valuable contribution to the science of hydraulics and, although academic, they are largely responsible for the conception by the Author of the subject of this Paper.

It is not intended here to take into account every factor governing varying flows, but to put forward a simple method, based on first principles, for determining the depth at any point in a channel where the velocity is increasing or decreasing in magnitude.

Notation.

Let Q denote the quantity of water flowing, in cubic feet per second.
,, v ,, velocity of the stream in the channel, in feet per second.
,, g ,, acceleration due to gravity, in feet per second per second.
,, d ,, depth of water in channel, in feet.
,, a ,, cross-sectional area of the stream in the channel, in square feet.
,, $\frac{v^2}{2g}$,, velocity-head, in feet.
,, h ,, height of the channel-invert above datum, in feet.
,, S ,, slope of the channel-invert, in decimals of a foot per foot length of channel.
,, i ,, energy lost by friction, in feet per foot length of channel.
,, E_s ,, specific energy, $\left(d + \frac{v^2}{2g}\right)$.
,, E_T ,, total energy, $\left(d + \frac{v^2}{2g} + h\right)$.
,, $\triangle E_s$,, increase in specific energy between two predetermined depths of water.
,, L ,, length of the channel, in feet.
,, $\triangle L = \frac{\triangle E_s}{S - i}$ denote the length of channel between two predetermined depths of water, which is positive when measured downstream and negative when measured upstream.

The Specific Energy.

Moving water, like any other moving body, possesses kinetic energy and potential energy. The potential energy can be divided into pressure-energy and position-energy; the pressure-energy is

measured from the invert of the channel to the water-surface and the position-energy is measured from the invert of the channel to the predetermined datum. The kinetic energy is the square of the velocity divided by twice the acceleration due to gravity. The sum of the pressure-energy and the kinetic energy is here termed the "specific energy," and the sum of the specific energy and position-energy is termed the "total energy."

By Bernouilli's theorem the total energy is constant for all sections of a moving stream in which there are no losses by friction or other causes. Considering Bernouilli's hypothetical stream, it is evident that as the potential energy becomes less, the specific energy increases; that is, the depth of water and velocity change as the water passes down the channel. There are, however, energy-losses in all channels, and the velocity at which the loss of energy per foot run is equal to the specific energy gained per foot run of channel can be found from any of the well-known formulas; in this condition the specific energy is constant.

For any type of channel the specific energy for various flows can be plotted against varying depths of water in the channel, as shown n *Fig. 1* (p. 290).

The Critical Depth.

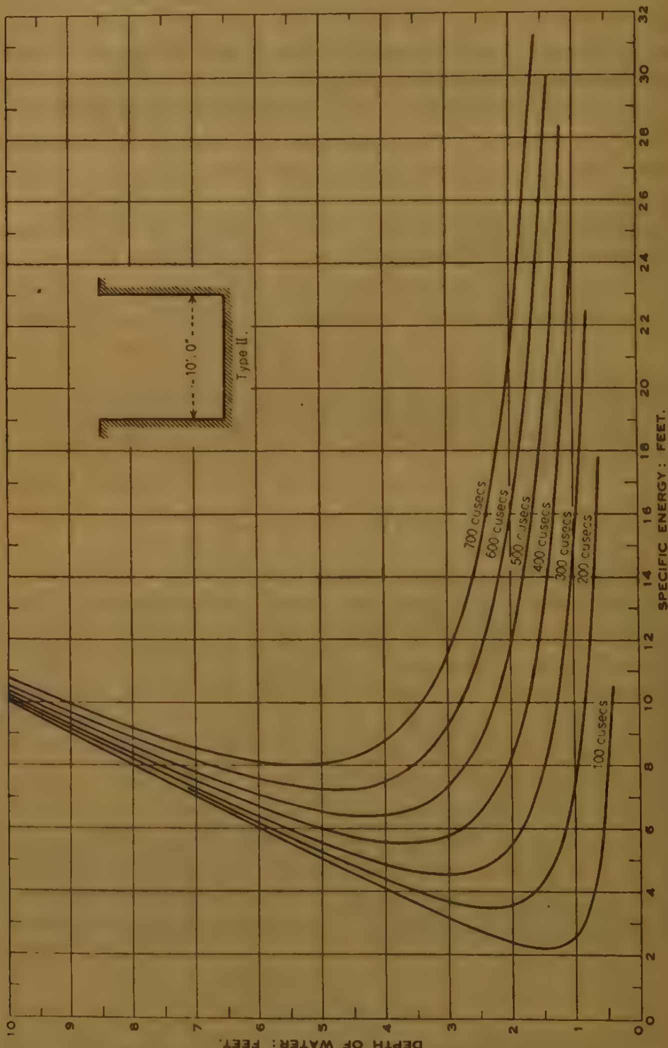
It will be observed that for each flow there is a depth at which he specific energy is a minimum, and it is also noteworthy that for ll other values of the specific energy there are two alternative lepths of water. The depth at which the specific energy is a ninimum is termed the "critical depth," and a flow at that depth s referred to as "critical flow," a flow at a depth greater than the ritical depth is referred to as "tranquil flow," and a flow at a depth ess than the critical depth is referred to as "rapid flow." The slope f channel to maintain a constant velocity at the critical depth is eferred to as the "critical slope," a slope to maintain a constant elocity at a depth greater than the critical depth is referred to as a "gradual slope," and a slope to maintain a constant velocity at a lepth less than the critical depth is referred to as a "steep slope."

Entrance-Conditions.

Let a channel be considered which passes a given quantity of water om a reservoir or tank. Assuming that there are no losses due to iction, eddy-currents or other causes, the total energy in the hannel will be equal to the total energy in the reservoir. The elocity in the channel will be greater than the velocity of approach

in the reservoir, and therefore the kinetic energy in the channel will be greater than that in the reservoir by an amount equal to the fall in the level of the water-surface from the tank to the channel.

Fig. 1.



SPECIFIC-ENERGY CURVE FOR A CHANNEL OF TYPE II.

Further, since the total energies in the reservoir and channel r spectively are equal, the specific energy in the reservoir will be equ to the specific energy in the channel plus the rise in elevation of th channel-invert above the reservoir-bed. If the velocity of approa

in the reservoir is small enough to be neglected, the height of the water-surface in the reservoir above the invert-level of the channel is equal to the specific energy in the channel. From this it is clear that the smaller the specific energy the smaller the head of water above the sill or invert of the channel, and, provided that there is no backing-up in the channel, the depth of water in the channel will be the critical depth. There are, however, considerable losses of energy as the water passes from a reservoir to a channel, especially where there are obstructions such as bridge-piers or sharp corners. In such cases the specific energy in the channel will differ from that in the reservoir less the height of the channel-invert above the reservoir-bed by anything from 40 to 10 per cent. of the kinetic energy in the channel, and the value of this percentage can best be determined by experiment on a model, as there are no standard designs for such entrance-works.

Change in Slope of Invert.

Where a channel of gradual slope changes to one of steep slope, the depth of water at the sill or change of slope will be such that the specific energy is a minimum, namely, the critical depth, as this is the point at which the flow is no longer backed-up. This is independent of the steepness of the steep slope of the channel-invert. It follows from this that in any channel of gradual slope the depth of water at the free-outlet end will be the critical depth for that quantity of water flowing.

Where a channel of steep slope changes to one of gradual slope, one of three things may occur, according to the circumstances. In all three cases the depth of water at the change of slope will be less than the critical depth, and the water will increase in depth as it flows along the gradual-slope channel.

(*a*) If the length of the gradual-slope channel is such that the water discharges freely from it before the depth has attained to the critical depth, there is no great loss of energy due to the change of slope.

(*b*) If the depth in the gradual-slope channel is such that the specific energy at tranquil flow is approximately equal to that appertaining to the rapid flow at the upper end of this channel, then there will be a hydraulic jump at the change of flow, and a considerable loss of energy will result.

(*c*) If the outlet flow from the gradual-slope channel is tranquil flow, but not of sufficient depth to cause a hydraulic

jump, then a hydraulic swell or standing wave will be produced, and the loss of energy will be somewhat less than in the case of the hydraulic jump.

When a channel of steep slope changes to one of critical slope, the depth of flow increases gradually until it becomes the critical depth, and hence there is no great loss in energy in the change of slope.

When a channel of critical slope changes to one of gradual slope, the depth of flow is again increased gradually, and finally falls off to the critical depth at the free-outlet end. Thus, if it is desired to change a channel of steep slope to one of gradual slope without the loss of energy and the formation of a barrier to floating objects inherent in the hydraulic jump, a length of channel of critical slope can be arranged between the steep-slope and gradual-slope channels. It must be remembered, however, that such an arrangement which is suitable for one flow may not hold good for other flows that may be experienced.

Finding the Depth of Water at any Point in a Channel.

Having now determined the type of flow that will result from a given flow in a predetermined channel, the distance between various depths of flow can be found.

In the case of the channel of critical slope the water enters at the critical depth and maintains that depth throughout the entire length of the channel. The specific energy is constant at all sections, and therefore the loss in total energy per foot run due to friction is equal to the loss in position-energy per foot run. Considering it from another point of view, the energy transformed per foot run from position energy to specific energy is equal to the energy lost per foot run by friction. This energy lost per foot run is often denoted by the letter i as in the well-known Chezy formula $v = c\sqrt{mi}$.

Tranquil Flow.

The slope of the invert, S, measured in decimals of a foot per foot length of channel, is less than the value of i for the depth of water in the channel at the inlet end, that is, the specific energy lost by friction per foot run is greater than that gained by fall in elevation, and, consequently, the net specific energy decreases the further from the inlet end the cross-section of the stream is taken, and it becomes a minimum at the free-outlet end, at which the depth is therefore the critical depth.

Example I.—Taking a channel of Type I (Appendix I, *Fig. 2*,

p. 308), 1,500 feet long at an invert slope S of 1 in 1,000 (0·001) and passing a flow of 900 cusecs, it is required to find the depth of water at the inlet end.

The critical depth for a flow of 900 cusecs in a channel of Type I is 4·9 feet (Appendix I, *Fig. 2*, p. 308), and taking Barnes's formula for canals and rivers, the value for i at 900 cusecs and 4·9 feet depth is 0·0067 (Appendix III, Table X), which is greater than S. The flow, therefore, will be tranquil and the free-outlet end will be at the critical depth. Since S (the gain in specific energy per foot run) is less than i (the loss in specific energy per foot run), the net gain, measured downstream, will be negative. As the depth of water is constantly changing the farther downstream the cross-sections are taken, the value of i will also be changing, and to account for this fact small changes in depth of water must be considered separately and the value of i for the average of such depths must be taken in the respective lengths of channel. This can be best explained by reference to Table I:—

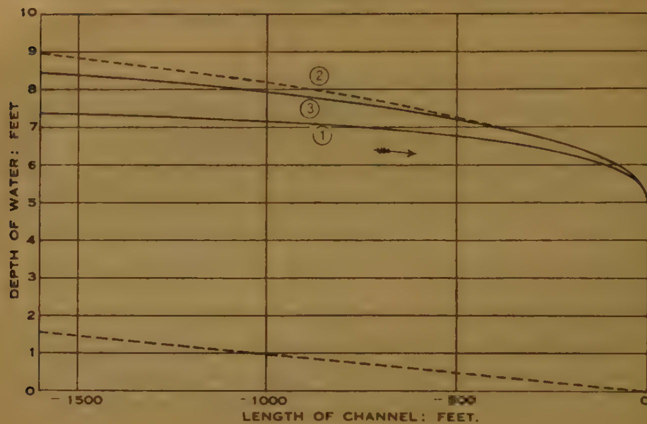
TABLE I.

$S = 0{\cdot}001$.

Col. (1)	Col. (2)	Col. (3)	Col. (4)	Col. (5)	Col. (6)	Col. (7)
Depth: feet.	Specific energy, E_S: feet.	Gain in specific energy, ΔE_S: feet.	i.	$S - i$.	$\Delta L = \frac{\Delta E_S}{S - i}$: feet.	L: feet.
4·9	6·641					0
		0·026	0·00578	−0·00478	−5·4	
5·2	6·667					−5·4
		0·047	0·00487	−0·00387	−12·1	
5·4	6·714					−17·5
		0·069	0·00424	−0·00324	−21·3	
5·6	6·783					−38·8
		0·086	0·00363	−0·00263	−32·7	
5·8	6·869					−71·5
		0·098	0·003159	−0·002159	−45·5	
6·0	6·967					−117·0
		0·297	0·002434	−0·001434	−207	
6·5	7·264					−324·0
		0·347	0·001762	−0·000762	−455	
7·0	7·611					−779·0
		0·384	0·001368	−0·000368	−1042	
7·5	7·995					−1819·0

If now the values of L in Col. (7) be plotted against their respective depths in Col. (1), a surface-curve results, as shown in *Fig. 3* (p. 294) by curve No. 1. Curve No. 2 represents the water-surface for the same flow and slope as No. 1, but taking into account the slope of

Fig. 3.



the invert, and curve No. 3 represents the same flow, but with an invert-slope of zero, the details of which are shown in Table II :—

TABLE II.

$S = 0{\cdot}0.$

Col. (1)	Col. (2)	Col. (3)	Col. (4)	Col. (5)	Col. (6)	Col. (7)
Depth : feet.	Specific energy, E_s : feet.	Gain in specific energy, ΔE_s : feet.	i.	$S - i$.	$\Delta L = \frac{\Delta E_s}{S - i}$ feet.	L : feet.
4·9	6·641					0
		0·026	0·00578	−0·00578	− 4·5	
5·2	6·667					− 4·5
		0·047	0·00487	−0·00487	− 9·6	
5·4	6·714					−14·1
		0·069	0·00424	−0·00424	−16·2	
5·6	6·783					−30·3
		0·086	0·00363	−0·00363	−23·7	
5·8	6·869					−54·0
		0·098	0·003159	−0·003159	−31	
6·0	6·967					−85·0
		0·397	0·002434	−0·002434	−122	
6·5	7·264					−207
		0·347	0·001762	−0·001762	−197	
7·0	7·611					−404
		0·384	0·001368	−0·001368	−281	
7·5	7·995					−685
		0·411	0·001027	−0·001027	−401	
8·0	8·406					−1086
		0·430	0·000789	−0·000787	−546	
8·5	8·836					−1632

It is interesting to note here that by dropping the invert-level by 1 foot 7 inches at 1,600 feet from the free-outlet end, the water-surface level at that section is lowered by only 6 inches, as shown by the difference in level of curves Nos. 2 and 3. Conversely, if a river or channel (of the type chosen for this example) of horizontal, or nearly horizontal, bed silts up gradually from nothing at the mouth to 1 foot 7 inches at 1,600 feet upstream, then the flood-level at 900 cusecs is increased by only 6 inches.

Rapid Flow.

The slope of the invert, S, is greater than the loss of energy, i, at the critical depth and consequently the net specific energy increases the further from the inlet end the cross-section of the stream is taken, and becomes a maximum when the depth is so reduced as to increase the value of i to be equal to that of S. The energy is a minimum at the inlet end, and therefore at the critical depth at that section.

Example II.—In a channel of Type I (Appendix I, *Fig. 2*, p. 308), with a gradient of 1 in 50, that is $S = 0{\cdot}02$, the flow is 700 cusecs. From Appendix III, Table X, it can be seen that, provided the channel is long enough, the depth will become constant at 3·2 feet, which is less than the critical depth of 4·25 feet. The flow will, therefore, be rapid, and the depth of water at the inlet end will be 4·25 feet. It is required to know at what distance from the origin "uniform" flow commences.

Since S, the slope of the invert, is such that the specific energy

TABLE III.

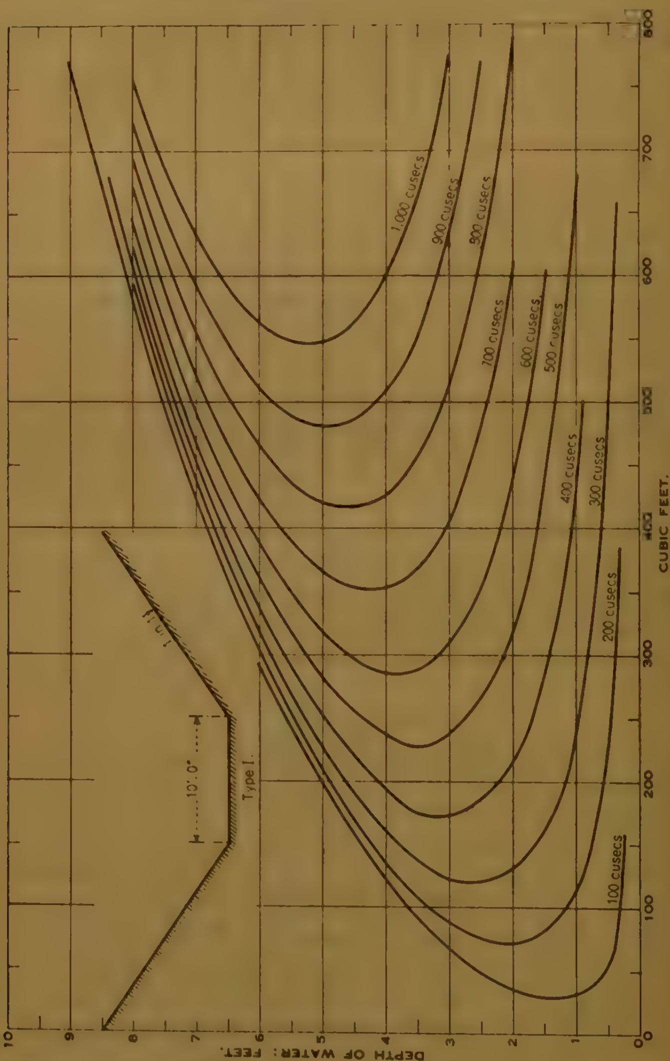
$S = 0{\cdot}02$.

Depth of water: feet.	E_S.	ΔE_S.	i.	$S - i$.	$\dfrac{\Delta E_S}{S - i}$.	L: feet.
4·25	5·820					0
		0·002	0·0070	0·0130	0·154	
4·20	5·822					0·2
		0·034	0·0078	0·0112	3·040	
4·00	5·856					3·2
		0·079	0·0096	0·0104	7·6	
3·80	5·935					10·8
		0·144	0·0118	0·0082	17·6	
3·60	6·079					28·4
		0·214	0·0146	0·0054	39·6	
3·40	6·293					68·0
		0·294	0·0182	0·0018	163	
3·20	6·587					231·0

gained at the expense of the position-head is greater than the energy lost by friction, the net specific energy gained is $S - i$.

The length of channel of non-uniform flow is therefore 231 feet,

Fig. 4.



JUMP-CURVES FOR A CHANNEL OF TYPE I.

(Table III) and any length of channel beyond this will be running at a uniform depth of 3·2 feet so long as the slope remains the same and there are no bends or other obstructions.

The Hydraulic Jump.

It has been stated above that under certain conditions a hydraulic jump occurs at the change from steep slope to gradual slope of the

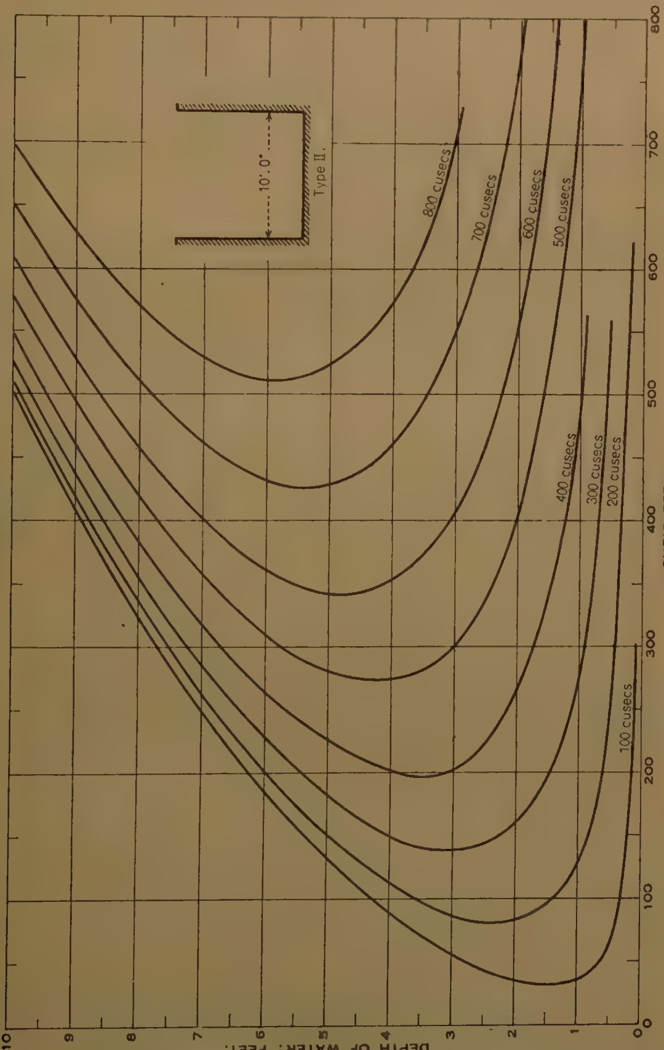


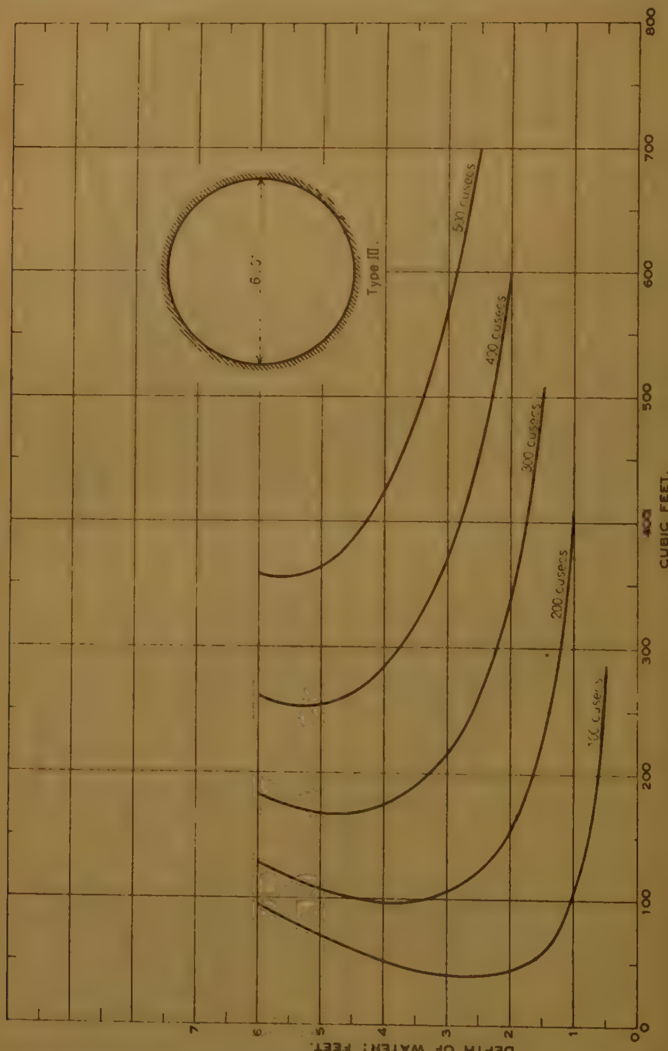
Fig. 5.

Jump-Curves for a Channel of Type II.

channel, and curves have been plotted in *Figs. 4, 5* and *6*, from which the height of jump can be read. These curves are calculated from a formula relating to channels with horizontal beds, but

can be taken as reasonably correct for a channel of gradual slope in designing for a model, or where exact measurements are not of great importance. They are plotted with abscissae representing (momen-

Fig. 6.



JUMP-CURVES FOR A CHANNEL OF TYPE III.

tum per second + total force), stated in terms of cubic feet of water, as this expression remains constant during the hydraulic jump.

Example III.—Given a channel of Type II (Appendix I, *Fig. 2*,

p. 308), having a slope of $S = 0{\cdot}05$ for a length of 52 feet, and then changing to one of $S = 0{\cdot}001$ for a length of 268 feet, making a total length of 320 feet, and discharging into a reservoir at its lower end with a water-surface level 7 feet above channel-invert level, it is required to know at what point the hydraulic jump would occur with a flow of 700 cusecs.

The figures are set out in Tables IV, V and VI :—

TABLE IV.

$S = 0{\cdot}05$.

Depth of water : feet.	E_S.	ΔE_S.	i.	$S - i$.	$\frac{\Delta E_S}{S - i}$.	L: feet.
5·4	8·009					0
		0·005	0·0050	0·0450	0·1	
5·2	8·014					0·1
		0·030	0·0055	0·0445	0·7	
5·0	8·044					0·8
		0·058	0·0062	0·0438	1·3	
4·8	8·102					2·1
		0·094	0·0069	0·0431	2·2	
4·6	8·196					4·3
		0·134	0·0078	0·0422	3·2	
4·4	8·330					7·5
		0·183	0·0089	0·0411	4·4	
4·2	8·513					11·9
		0·242	0·0100	0·0400	6·1	
4·0	8·755					18·0
		0·314	0·0114	0·0386	8·1	
3·8	9·069					26·1
		0·402	0·0132	0·0368	10·9	
3·6	9·471					37·0
		0·511	0·0157	0·0343	14·9	
3·4	9·982					51·9

TABLE V.

$S = 0{\cdot}001$.

Depth of water : feet.	E_S.	ΔE_S.	i.	$S - i$.	$\frac{\Delta E_S}{S - i}$.	L: feet.
3·4	9·982					52
		−0·489	0·0157	−0·0147	33·2	
3·6	9·471					85·2
		−0·598	0·0132	−0·0122	49·0	
3·8	9·069					134·2
		−0·686	0·0114	−0·0104	66·0	
4·0	8·755					200·2
		−0·758	0·0100	−0·0090	84·2	
4·2	8·513					284·4

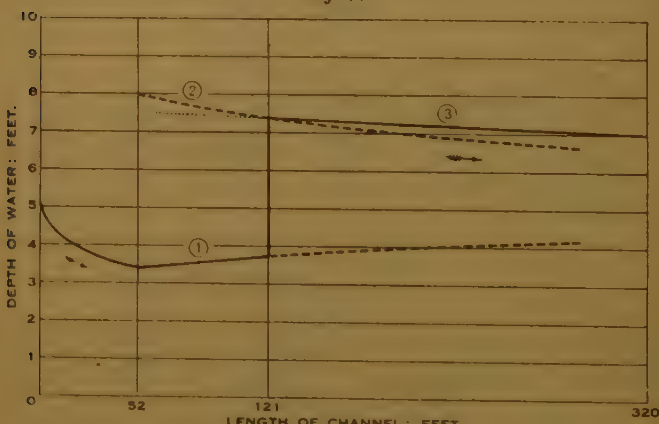
TABLE VI.

$S = 0{\cdot}001.$

Depth of water. feet.	E_s.	ΔE_s.	i.	$S - i$.	$\frac{\Delta E_s}{S - i}$.	L. feet.
7·0	8·553					320
		0·300	0·00215	−0·00115	−261	
7·5	8·853					59

In *Fig.* 7 is shown the water-surface curve plotted from Table IV in the length of channel from zero to 52 feet, and curve No. 1 plotted from Table V. Curve No. 2 is arrived at from the jump-curves shown in *Fig.* 5, and shows the level up to which the water-surface will jump if obstructed at any cross-section. Curve No. 3 is the water surface for tranquil flow, terminating at a depth of 7 feet as it leaves the channel, and is plotted from Table VI.

Fig. 7.



The rapid flow represented by curve No. 1 is obstructed by the 7 feet of water in the reservoir, and consequently a jump is formed and is in equilibrium where curves Nos. 2 and 3 cross. Thus the position of the hydraulic jump for a flow of 700 cusecs is at a point 121 feet from the upstream end of the channel.

In *Fig.* 7 the jump is indicated by a vertical line, as the means for

determining the length of the jump has yet to be discovered. The jump itself appears to be somewhat complex in nature, and accurate measurements are difficult to obtain as the surface is constantly on the move.

If instead of a channel there were a rectangular culvert 10 feet wide by 5 feet 6 inches deep for the first 52 feet, 4 feet deep for the remaining 268 feet, and with a free-outlet end, then with a flow of 700 cusecs the water-surface curve No. 1 (*Fig. 7*), would touch the roof of the culvert at 200 feet. This obstruction would produce the conditions necessary to form a jump, but the roof would prevent one from taking place at this section and so the culvert would quickly fill up. In filling up, a tidal wave would travel upstream, driving out and drawing out the air. In this state the culvert would be functioning as a pipe with an overall hydraulic slope greater than 0·001, which is the gradient of the lower part of the culvert; the discharge would increase accordingly and would become greater than 700 cusecs, which is the rate of inflow. It is easy to understand that under these circumstances there would be pulsations with varying pressures on the roof of the culvert.

Under similar circumstances a brick sewer with a change of slope from steep to gradual may be subject to such pulsations, which must inevitably be deleterious to the water-tightness of the structure.

If the culvert be continued and turned down into the feeding reservoir so that the end is well below water-level, the siphonic action will continue and function as in a siphon spillway.

Stilling-Pools.

In river-works it is often necessary to discharge quantities of water at high velocities into the river, with consequent danger of scour of the bed near to the works. Clearly, the smaller the velocity of entrance to the river the less scour there will be, and this can be brought about by taking advantage of the energy-absorbing properties of the hydraulic jump. Having arrived at the depth of flow in the channel just prior to discharge, the height of the jump can be read off the curves and a barrier can be built across the channel sufficient to back up the water to the required height to form the jump. This has the possible disadvantage that the water has to fall again to river-bed level, thus gaining velocity. If this is so, a sump can be made in which the jump will form and from which the water will leave with tranquil flow.

Scale-Ratio.

The Tables and Figures have been compiled to suit most common types of channels or conduits, and the chart in *Fig. 8* is for use in determining the factor by which to multiply the flows given in Appendixes I to III to keep them in proportion to the linear dimensions of the respective channels.

Fig. 8.

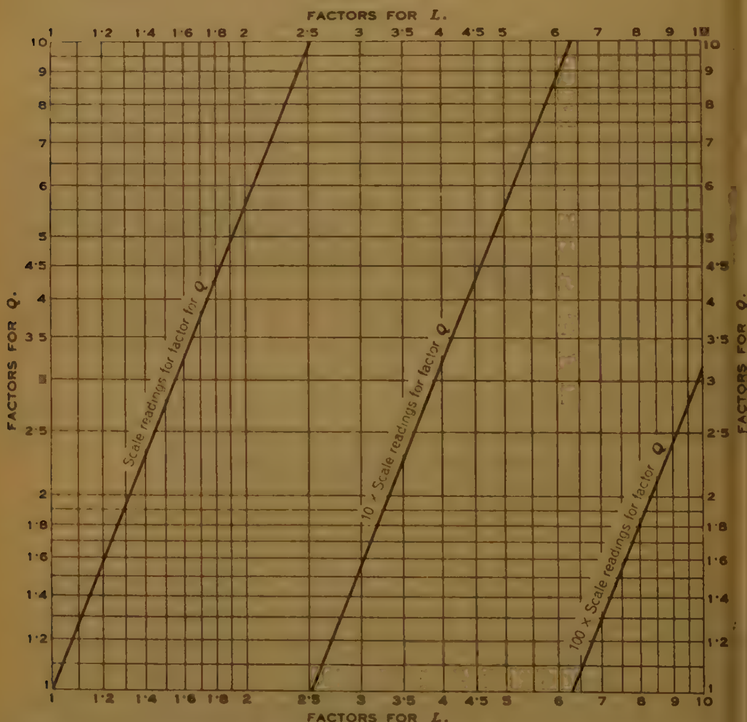


Chart to Determine Proportionate Flows in relation to Various Scales.

Example IV.—A channel of Type II, 18 feet wide, is to be narrowed down to 9 feet wide. It is required to find the fall in level of th invert from one end to the other of the tapering portion in order t maintain a constant depth of water of 5 feet with a flow of 600 cusecs

(*a*) To find the specific energy in the 18-foot wide channe it is necessary to turn to *Fig. 8* and, opposite th

scale-ratio of $\frac{18}{10}$, or 1·8, to read off the flow-ratio of 4·33. This gives for 600 cusecs in an 18-foot channel a flow equivalent to $\frac{600}{4 \cdot 33}$, or 138·5 cusecs in an $\frac{18}{1 \cdot 8}$, or 10-foot channel, at a depth of $\frac{5}{1 \cdot 8} = 2 \cdot 78$ feet.

The specific energy for the latter can then be taken from Appendix III, which gives 3·226 feet. This is equivalent to a specific energy of $1 \cdot 8 \times 3 \cdot 226$

$$= 5 \cdot 807 \text{ feet in the 18-foot channel.}$$

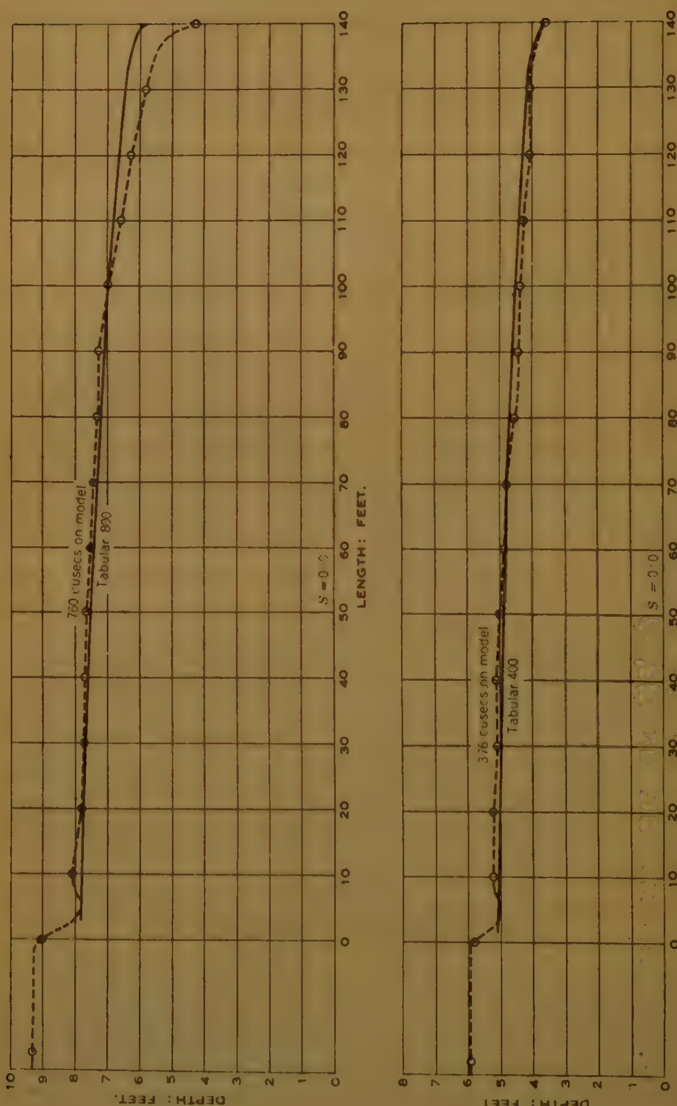
(*b*) To find the specific energy in the 9-foot channel, opposite the scale-ratio of $\frac{10}{9}$, or 1·11, in *Fig. 8*, the flow-ratio of 1·3 must be read off. This gives for 600 cusecs in a 9-foot channel a flow equivalent to $600 \times 1 \cdot 3$, or 780 cusecs in a $9 \times 1 \cdot 11$ or 10-foot channel, at a depth of $5 \times 1 \cdot 11$, or 5·55 feet. The specific energy for the latter can then be taken from Appendix III, as for the 18-foot channel, and gives 8·621 feet, which is equivalent to $\frac{8 \cdot 621}{1 \cdot 11} = 7 \cdot 767$ feet in the 9-foot channel.

(*c*) To allow for eddy and frictional losses, it is necessary to add, say, 10 per cent. to the theoretical downstream specific energy, making it equal to $7 \cdot 767 + 0 \cdot 287 = 8 \cdot 054$ feet. Then the required increase in specific energy at the expense of the position-energy is $8 \cdot 054 - 5 \cdot 807 = 2 \cdot 247$ feet, which is the necessary fall in elevation of the invert from the 18-foot to 9-foot width ends of the tapered length of channel to fulfil the given requirements.

Experiments on Models.

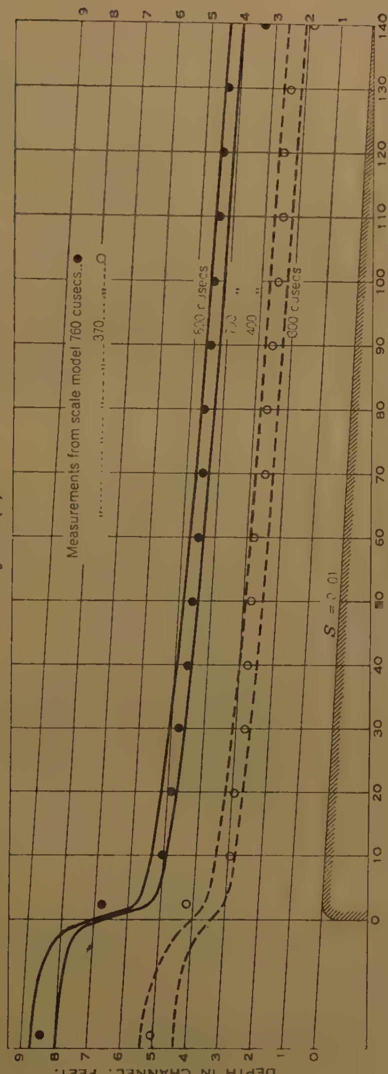
A model of a channel of Type II was constructed at a scale of one-twentieth that shown in the Appendixes. Measured flows of water were passed down the channel at different slopes of invert, and depths of water were taken at equal intervals and were plotted as shown in *Figs. 9, 10* (*a*) and *10* (*b*) (pp. 304–6), where the comparisons between the tabulated theoretical depths and the actual measured depths are shown.

Figs. 9.



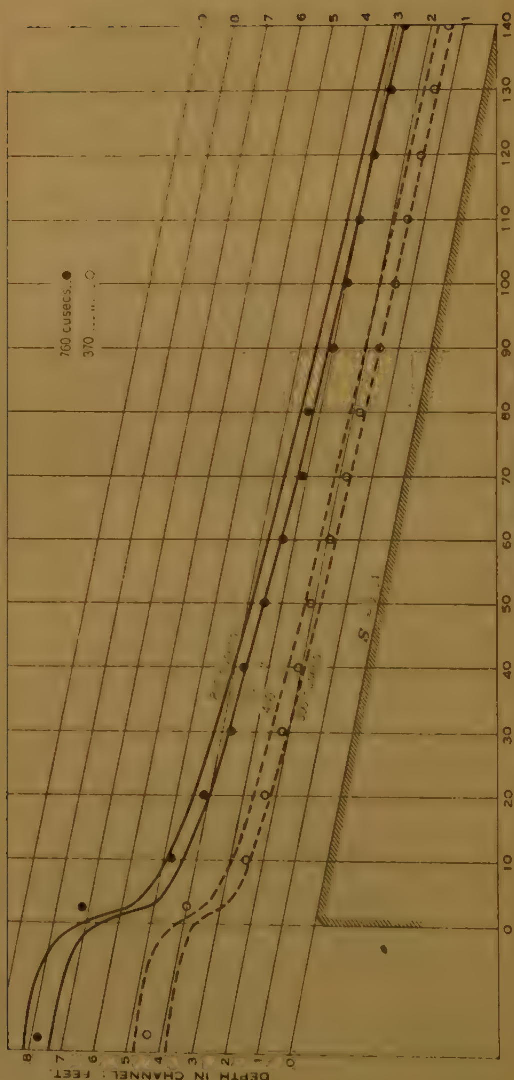
EXPERIMENTS ON $\frac{1}{20}$TH SCALE MODEL OF A CHANNEL OF TYPE II: TRANQUIL FLOW.

Fig. 10 (a).



EXPERIMENTS ON $\frac{1}{20}$TH SCALE MODEL OF A CHANNEL OF TYPE II: RAPID FLOW.

Fig. 10 (b).



EXPERIMENTS ON $\frac{1}{20}$TH SCALE MODEL OF A CHANNEL OF TYPE II : RAPID FLOW.

Conclusion.

In conclusion, the Author, whilst admitting the somewhat theoretical nature of the subject, claims that the results obtained by the foregoing method bear a close resemblance to experiments on small models, and hopes that any engineers who have measurements of non-uniform flows on full-size works will make such measurements known in the Correspondence on this Paper so that a fair comparison between the theory and facts may be established.

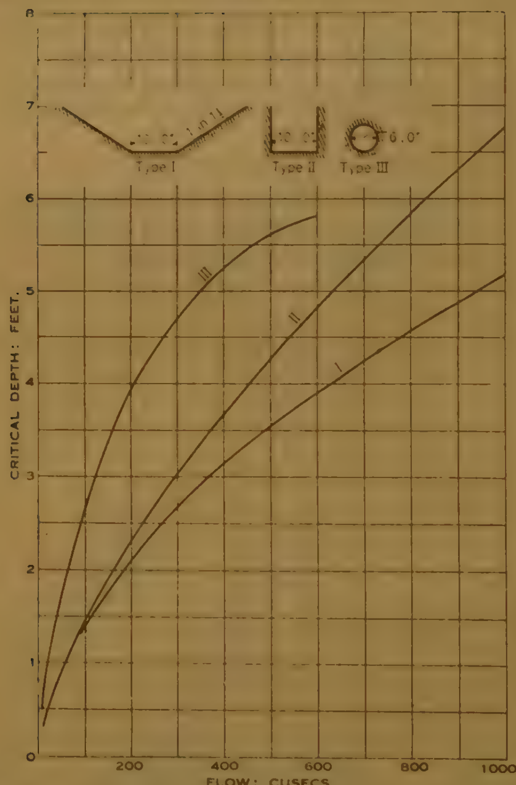
This Paper was written at the suggestion of Mr. J. K. Swales, M.C., M. Inst. C.E., and the Author wishes to express his thanks to him for the facilities afforded for carrying out model experiments on the subject.

The Paper is accompanied by ten sheets of drawings, from which the Figures in the text and Appendixes have been prepared, by two photographs, and by the following Appendixes.

[Appendixes

APPENDIX I.

Fig. 2.



CRITICAL-DEPTH CURVES FOR CHANNELS OF TYPES I, II, AND III.

NOTE.—The Institution as a body is not responsible either for the statements made, or for the opinions expressed, in the Papers published.

Table VII.

Specific Energy in a Channel of Type I (*Fig. 2*, Appendix I), expressed in Feet, for Various Depths and Flows of Water.

Depth of water: feet.	100 cusecs.	200 cusecs.	300 cusecs.	400 cusecs.	500 cusecs.	600 cusecs.	700 cusecs.	800 cusecs.	900 cusecs.	1,000 cusecs.
0·2	36·726									
0·4	9·048									
0·6	4·235	15·603	33·239							
0·8	2·731	8·722	18·174	31·688						
1·0	2·175	5·701	11·578	19·805	30·450					
1·2	1·974	4·296	8·166	13·583	20·549	29·063	39·124			
1·4	1·941	3·562	6·265	10·049	14·913	20·859	27·886			
1·6	1·994	3·174	5·150	7·911	11·461	15·800	20·927	26·844	33·549	
1·8	2·097	2·989	4·474	6·555	9·230	12·500	16·363	20·822	25·807	31·522
2·0	2·230	2·921	4·072	5·683	7·754	10·286	13·278	16·730	20·643	25·016
2·2	2·382	2·926	3·835	5·106	6·741	8·738	11·999	13·824	16·911	20·362
2·4	2·545	2·982	3·709	4·726	6·035	7·634	9·525	11·705	14·177	16·940
2·6	2·719	3·077	3·672	4·506	5·579	6·889	8·438	10·225	12·251	14·514
2·8	2·899	3·194	3·687	4·378	5·265	6·350	7·632	9·111	10·787	12·661
3·0	3·082	3·329	3·739	4·314	5·054	5·957	7·025	8·257	9·654	11·214
3·2	3·269	3·477	3·822	4·306	4·928	5·695	6·587	7·624	8·800	10·113
3·4	3·459	3·636	3·931	4·345	4·876	5·526	6·293	7·179	8·183	9·305
3·6	3·651	3·802	4·055	4·409	4·865	5·421	6·079	6·838	7·698	8·659
3·8	3·844	3·974	4·192	4·497	4·889	5·368	5·935	6·588	7·329	8·157
4·0	4·038	4·152	4·341	4·606	4·947	5·364	5·856	6·425	7·069	7·789
4·2	4·233	4·332	4·498	4·730	5·027	5·392	5·822	6·318	6·881	7·510
4·4	4·429	4·516	4·662	4·866	5·128	5·448	5·826	6·263	6·757	7·310
4·6	4·626	4·703	4·831	5·012	5·243	5·526	5·860	6·246	6·683	7·172
4·8	4·823	4·891	5·005	5·164	5·368	5·618	5·914	6·255	6·642	7·073
5·0	5·020	5·081	5·182	5·324	5·506	5·729	5·992	6·296	6·640	7·025
5·2	5·218	5·272	5·363	5·490	5·653	5·852	6·087	6·359	6·667	7·011
5·4	5·416	5·465	5·546	5·660	5·805	5·984	6·195	6·438	6·714	7·022
5·6	5·615	5·658	5·731	5·834	5·965	6·126	6·316	6·535	6·783	7·061
5·8	5·813	5·853	5·919	6·011	6·130	6·275	6·447	6·645	6·869	7·120
6·0	6·012	6·048	6·107	6·191	6·299	6·430	6·585	6·764	6·967	7·194
6·5	6·510	6·538	6·585	6·651	6·736	6·840	6·962	7·104	7·264	7·438
7·0	7·008	7·030	7·068	7·121	6·189	7·271	7·369	7·483	7·611	7·754
7·5	7·506	7·524	7·555	7·598	7·653	7·720	7·800	7·891	7·995	8·111
8·0	8·005	8·020	8·045	8·080	8·125	8·180	8·246	8·321	8·406	8·501
8·5	8·504	8·517	8·537	8·566	8·604	8·650	8·703	8·766	8·836	8·915
9·0	9·003	9·014	9·031	9·056	9·087	9·125	9·170	9·222	9·281	9·347
9·5	9·502	9·512	9·526	9·547	9·573	9·605	9·643	9·687	9·737	9·793
10·0	10·002	10·010	10·022	10·040	10·062	10·089	12·122	10·159	10·201	10·248

Table VIII.

Specific Energy in a Channel of Type II (*Fig. 2*, Appendix I) expressed in Feet, for Various Depths and Flows of Water.

Depth of water: feet.	100 cusecs.	200 cusecs.	300 cusecs.	400 cusecs.	500 cusecs.	600 cusecs.	700 cusecs.	800 cusecs.
0·4	10·105	39·220						
0·6	4·913	17·853	39·420					
0·8	3·326	10·505	22·636	39·620				
1·0	2·553	7·211	14·975	25·845	39·820	56·901		
1·2	2·278	5·513	10·905	18·453	28·158	40·020	54·038	
1·4	2·192	4·569	8·530	14·076	21·207	29·922	40·132	52·104
1·6	2·207	4·026	7·059	11·305	16·764	23·436	31·322	40·420
1·8	2·279	3·717	6·113	9·468	13·781	19·053	25·284	32·472
2·0	2·388	3·553	5·494	8·211	11·705	15·975	21·022	26·845
2·2	2·521	3·483	5·087	7·333	10·221	13·750	17·920	22·733
2·4	2·670	3·478	4·826	6·713	9·140	12·105	15·610	19·673
2·6	2·830	3·519	4·667	6·275	8·343	10·869	13·855	17·301
2·8	2·998	3·592	4·583	5·969	7·752	9·930	12·505	15·476
3·0	3·173	3·690	4·553	5·761	7·313	9·211	11·454	14·042
3·2	3·352	3·807	4·565	5·626	6·991	8·659	10·630	12·905
3·4	3·534	3·937	4·609	5·549	6·758	8·236	9·982	11·997
3·6	3·720	4·079	4·678	5·517	6·595	7·913	9·471	11·268
3·8	3·908	4·230	4·768	5·521	6·488	7·671	9·069	10·682
4·0	4·097	4·388	4·873	5·553	6·426	7·494	8·755	10·211
4·2	4·288	4·552	4·992	5·608	6·401	7·369	8·513	9·834
4·4	4·480	4·721	5·122	5·683	6·405	7 288	8·330	9·533
4·6	4·673	4·894	5·260	5·774	6·453	7·224	8·196	9·297
4·8	4·867	5·070	5·407	5·878	6·485	7·226	8·102	9·113
5·0	5·062	5·248	5·559	5·994	6·553	7·236	8·044	8·975
5·2	5·257	5·430	5·717	6·119	6·636	7·267	8·014	8·875
5·4	5·453	5·613	5·879	6·252	6·731	7·317	8·009	8·808
5·6	5·650	5·798	6·046	6·392	6·838	7·383	8·026	8·769
5·8	5·846	5·985	6·215	6·539	6·954	7·462	8·062	8·754
6·0	6·043	6·173	6·388	6·690	7·078	7·553	8·114	8·761
6·5	6·537	6·647	6·831	7·088	7·419	7·823	8·301	8·852
7·0	7·032	7·127	7·285	7·507	7·792	8·141	8·553	9·028
7·5	7·528	7·610	7·748	7·942	8·190	8·494	8·853	9·267
8·0	8·024	8·087	8·218	8·388	8·607	8·873	9·189	9·553
8·5	8·521	8·586	8·693	8·844	9·037	9·274	9·553	9·876
9·0	9·019	9·077	9·173	9·307	9·479	9·690	9·939	10·227
9·5	9·517	9·569	9·655	9·775	9·930	10·119	10·343	10·601
10·0	10·016	10·062	10·140	10·248	10·388	10·559	10·761	10·994

APPENDIX II.

Table IX.

Specific Energy in a Conduit of Type III (*Fig. 2*, Appendix I), expressed in Feet, for Various Depths and Flows of Water.

Depth of water: feet.	100 cusecs.	200 cusecs.	300 cusecs.	400 cusecs.	500 cusecs.	600 cusecs.
0·8	33·474					
1·0	17·692					
1·2	11·152	41·009				
1·4	7·738	26·749				
1·6	5·842	18·569	39·781			
1·8	4·779	13·715	28·609			
2·0	4·211	10·845	21·901	37·379		
2·2	3·903	9·010	17·523	29·442		
2·4	3·769	7·876	14·721	24·304		
2·6	3·706	7·023	12·552	20·293	30·245	
2·8	3·721	6·484	11·088	17·535	25·823	
3·0	3·777	6·108	9·993	15·431	22·424	30·971
3·2	3·860	5·840	9·139	13·758	19·697	26·956
3·4	3·972	5·690	8·552	12·559	17·711	24·008
3·6	4·099	5·594	8·086	11·575	16·061	21·544
3·8	4·241	5·565	7·771	10·859	14·830	19·684
4·0	4·392	5·568	7·529	10·274	13·803	18·116
4·2	4·549	5·597	7·343	9·788	12·931	16·773
4·4	4·714	5·655	7·223	9·419	12·241	15·691
4·6	4·884	5·734	7·152	9·137	11·690	14·809
4·8	5·062	5·846	7·153	8·983	11·336	14·213
5·0	5·243	5·970	7·183	8·881	11·065	13·733
5·2	5·427	6·107	7·241	8·828	10·868	13·362
5·4	5·615	6·258	7·331	8·883	10·765	13·125
5·6	5·805	6·418	7·441	8·873	10·715	12·965
5·8	5·998	6·592	7·583	8·969	10·752	12·930
6·0	6·194	6·777	7·748	9·108	10·856	12·993

[Appendix III *overleaf*.

APPENDIX III.

Table X.

Friction-Losses in a Channel of Type I (*Fig. 2*, Appendix I) (using Barnes's Formula for Canals and Rivers), expressed in Terms of Decimals of a Foot per Unit Foot Length of Channel, for Various Depths and Flows of Water.

Depth of water: feet.	100 cusecs.	200 cusecs.	300 cusecs.	400 cusecs.	500 cusecs.	600 cusecs.	700 cusecs.	800 cusecs.	900 cusecs.	1,000 cusecs.
0·7	0·1106	0·461								
0·9	0·0435	0·181								
1·1	0·0192	0·082	0·192							
1·3	0·0107	0·045	0·103	0·186						
1·5	0·0066	0·026	0·060	0·111	0·175					
1·7	0·0043	0·0175	0·038	0·070	0·112	0·159	0·218			
1·9	0·0028	0·0110	0·029	0·045	0·073	0·103	0·143	0·188		
2·1	0·0019	0·0075	0·017	0·031	0·047	0·069	0·095	0·126	0·163	
2·3	0·0013	0·0054	0·0125	0·022	0·035	0·052	0·068	0·089	0·118	0·145
2·5	0·0010	0·0041	0·0095	0·0165	0·026	0·039	0·051	0·069	0·088	0·108
2·7	0·00079	0·0031	0·0070	0·0130	0·020	0·029	0·039	0·053	0·067	0·082
2·9	0·00061	0·0024	0·0053	0·0100	0·0155	0·022	0·030	0·039	0·051	0·063
3·1	0·00046	0·0018	0·0042	0·0077	0·0120	0·0175	0·023	0·030	0·039	0·049
3·3	0·00037	0·0014	0·0034	0·0061	0·0096	0·0138	0·0182	0·024	0·031	0·039
3·5	0·00030	0·0012	0·0027	0·0049	0·0075	0·0109	0·0146	0·0192	0·025	0·031
3·7	0·000235	0·00095	0·0022	0·0039	0·0060	0·0087	0·0118	0·0155	0·020	0·025
3·9	0·000190	0·00077	0·0018	0·0031	0·0050	0·0070	0·0096	0·0127	0·016	0·020
4·1	0·000156	0·00064	0·00145	0·0025	0·0041	0·0058	0·0078	0·0104	0·013	0·0165
4·3	0·000130	0·00053	0·00121	0·0021	0·0034	0·0047	0·0063	0·0086	0·0109	0·0135
4·5	0·000110	0·00044	0·00101	0·0018	0·0028	0·0040	0·0054	0·0073	0·0091	0·0113
4·7	0·000095	0·00037	0·00085	0·00154	0·0024	0·0034	0·0046	0·0062	0·0078	0·0098
4·9	0·000079	0·00032	0·00073	0·00131	0·0020	0·0030	0·0040	0·0052	0·0067	0·0085
5·1	0·000067	0·000278	0·00062	0·00112	0·0017	0·0025	0·0035	0·0045	0·0057	0·0070
5·3	0·000058	0·000239	0·000535	0·00097	0·0014	0·0022	0·0030	0·0038	0·00487	0·0060
5·5		0·000205	0·000458	0·00083	0·00131	0·0018	0·0026	0·0032	0·00424	0·0051
5·7		0·000177	0·000395	0·00071	0·00112	0·0015	0·0022	0·0028	0·00363	0·0044
5·9		0·000151	0·000341	0·00061	0·00096	0·0014	0·0019	0·0025	0·00359	0·0038
6·25		0·000116	0·000269	0·00047	0·00074	0·0011	0·0015	0·0020	0·002534	0 0030
6·75		0·000086	0·000196	0·00035	0·00055	0·00081	0·00111	0·00146	0·001762	0·0023
7·25		0·000065	0·000146	0·00026	0·00041	0·00060	0·00081	0·00107	0·001368	0·00162
7·75		0·000050	0·000110	0·00020	0·00031	0·00045	0·00061	0·00080	0·001027	0·00123
8·25		0·000038	0·000085	0·00015	0·00024	0·00034	0·00046	0·00060	0·000789	0·00095
8·75			0·000065	0·000117	0·000185	0·000265	0·00036	0·00047	0·000600	0·00075
9·25			0·000052	0·000094	0·000135	0·000210	0·000285	0·000375	0·000480	0·00059
9·75			0·000041	0·000064	0·000116	0·000168	0·000225	0·000295	0·000380	0·00047

Table XI.

Friction-Losses in a Channel of Type II (*Fig. 2*, Appendix I) (using Barnes's Formula for Smooth Concrete), expressed in Terms of Decimals of a Foot per Unit Foot Length of Channel, for Various Depths and Flows of Water.

Depth of water: feet.	100 cusecs.	200 cusecs.	300 cusecs.	400 cusecs.	500 cusecs.	600 cusecs.	700 cusecs.	800 cusecs.
0·5	0·095	0·42						
0·7	0·033	0·14	0·34					
0·9	0·015	0·065	0·151	0·281				
1·1	0·0078	0·0343	0·082	0·150	0·241			
1·3	0·0047	0·0202	0·049	0·090	0·146	0·217		
1·5	0·0030	0·0130	0·0311	0·058	0·093	0·139	0·191	
1·7	0·00205	0·0090	0·0212	0·0399	0·065	0·095	0·130	0·175
1·9	0·00149	0·0066	0·0145	0·0288	0·0462	0·068	0·094	0·124
2·1	0·00109	0·0048	0·0112	0·0212	0·0341	0·050	0·069	0·094
2·3	0·00085	0·00364	0·00875	0·0140	0·0259	0·039	0·054	0·070
2·5	0·00066	0·00288	0·00682	0·0125	0·0201	0·0298	0·0419	0·055
2·7	0·00053	0·00229	0·00550	0·0099	0·0160	0·0235	0·0330	0·045
2·9	0·00043	0·00187	0·00448	0·0082	0·0130	0·0192	0·0270	0·036
3·1	0·00035	0·00152	0·00361	0·0068	0·0109	0·0159	0·0221	0·0292
3·3	0·00030	0·00129	0·00303	0·0057	0·0090	0·0132	0·0187	0·0249
3·5	0·00025	0·00109	0·00258	0·00479	0·0076	0·0112	0·0157	0·0208
3·7	0·000215	0·00093	0·00220	0·00409	0·0066	0·0095	0·0132	0·0177
3·9	0·000185	0·00080	0·00190	0·00355	0·0057	0·0084	0·0114	0·0152
4·1	0·000161	0·00070	0·00166	0·00301	0·0050	0·0073	0·0100	0·0121
4·3	0·000139	0·00062	0·00144	0·00269	0·0043	0·0064	0·0089	0·0116
4·5	0·000122	0·00054	0·00127	0·00233	0·0038	0·0056	0·0078	0·0102
4·7	0·000109	0·000484	0·00112	0·00210	0·0034	0·0050	0·0069	0·0091
4·9	0·000098	0·000430	0·00100	0·00187	0·00305	0·0044	0·0062	0·0081
5·1	0·000086	0·000382	0·00090	0·00166	0·00269	0·0040	0·0055	0·0073
5·3	0·000078	0·000349	0·00081	0·00143	0·00232	0·0036	0·0050	0·0067
5·5	0·000070	0·000313	0·00074	0·00134	0·00220	0·00323	0·0045	0·0060
5·7	0·000065	0·000285	0·000671	0·00124	0·00198	0·00298	0·0041	0·00546
5·9	0·000059	·0000258	0·000613	0·00111	0·00170	0·00270	0·00375	0·00499
6·25		0·000221	0·000528	0·00097	0·00157	0·00230	0·00320	0·00423
6·75		0·000183	0·000438	0·000795	0·00128	0·00189	0·00261	0·00349
7·25		0·000149	0·000360	0·000665	0·00105	0·00155	0·00215	0·00289
7·75		0·000122	0·000299	0·000549	0·00088	0·00130	0·00181	0·00241
8·25		0·000106	0·000254	0·000468	0·00075	0·00110	0·00152	0·00204
8·75		0·000092	0·000219	0·000405	0·00065	0·00095	0·00130	0·00178
9·25		0·000080	0·000190	0·000352	0·00057	0·00083	0·00114	0·00152
9·75		0·000070	0·000166	0·000310	0·00049	0·00072	0·00100	0·00133

Table XII.

Friction-Losses in a Conduit of Type III (*Fig. 2*, Appendix I) (usin Barnes's Formula for Well-Pointed Brickwork), expressed in Term of Decimals of a Foot per Unit Foot Length of Channel, for Variou Depths and Flows of Water.

Depth of water: feet.	100 cusecs.	200 cusecs.	300 cusecs.	400 cusecs.	500 cusecs.	600 cusecs.
0·9	0·00232	0·0103				
1·1	0·00096	0·00435				
1·3	0·00049	0·00217				
1·5	0·000252	0·00111				
1·7	0·000141	0·00063	0·00151			
1·9	0·000090	0·00040	0·00096	0·00181		
2·1	0·000061	0·000266	0·00064	0·00120		
2·3	0·000043	0·000190	0·00046	0·00085		
2·5		0·000140	0·000335	0·00063		
2·7		0·000106	0·000260	0·00047	0·00077	
2·9		0·000082	0·000201	0·00037	0·00059	
3·1		0·000065	0·000157	0·00029	0·00047	0·00071
3·3		0·000054	0·000128	0·00024	0·00038	0·00057
3·5		0·000047	0·000106	0·00021	0·00035	0·00047
3·7		0·000039	0·000089	0·00017	0·00028	0·00039
3·9		0·000033	0·000076	0·00015	0·000241	0·00034
4·1		0·000028	0·000065	0·00012	0·000196	0·00029
4·3			0·000055	0·000102	0·000169	0·00025
4·5			0·000050	0·000092	0·000150	0·00022
4·7			0·0000445	0·000082	0·000134	0·00020
4·9			0·0000413	0·000075	0·000123	0·000185
5·1			0·0000374	0·000071	0·000112	0·000170
5·3			0·0000359	0·000068	0·000108	0·000160
5·5			0·0000347	0·000065	0·000104	0·000155
5·7			0·0000349	0·000064	0·000109	0·000154
5·9			0·0000361	0·000062	0·000109	0·000165

ENGINEERING RESEARCH.

FOREST PRODUCTS RESEARCH.

The activities of the Forest Products Research Laboratory have continued to increase, according to the Report of the Board for the year 1936.

Previous work having shown the relation between timber quality and growth conditions in the case of oak, the investigation has been extended to home-grown ash, beech, and Sitka spruce. Strength is found to be related to the physico-chemical nature of the cell-walls rather than to the density and structure of the timber. Tropical timbers, whilst of strength equal to or greater than temperate timbers, appear to be in general less tough. The strengths of the more important structural timbers have been investigated. British Columbian Douglas fir is found to be both stronger and stiffer than Baltic redwood. Proceeding from the sapwood to the heart of English oak, the density is found to increase, and the strength to increase to an even greater extent.

A study of the moisture-relations of wood has shown that below a certain quantity the moisture is held by molecular sorption; with increase of moisture capillary sorption appears, and a still higher moisture-content influences the swelling and shrinkage of the timber. It has been possible to correlate the shrinkage with the hydrostatic tension causing the negative pressures in capillary action. Soaking with certain aqueous solutions has been found to be effective in reducing the movement or "working" under varying atmospheric conditions. A study has been made of air-seasoning and kiln-drying. A greater overall shrinkage is found to take place in timber dried at high temperatures.

The leaching-out of water-soluble preservatives has been investigated. A comparison of the creosoting of railway sleepers by the full-cell and by the empty-cell process has shown that whilst with the latter less creosote may be absorbed, penetration is far more uniform and reliable. The advantage of incising heartwood faces is emphasized. Long periods of seasoning before creosoting appear to be undesirable, as more creosote can be absorbed while the moisture-content is high. A distinction is made between the surface and the average moisture-contents. Charring or tarring of fence-posts appears to have little preservative value.

Other work includes a study of fire-resistance and fireproofing, wood-rots and borers, woodworking, box-testing, ply-woods, and glues.

FUEL RESEARCH.

The Report of the Fuel Research Board for the year ended 31 March, 1937, has appeared.

The work of the Coal Survey has continued. A scheme has been drawn up for the classification of all grades of coal below 3 inches in size marketed in the South and West Yorkshire areas. Research aimed at a reduction in the percentage of coal-dust has been carried out on the breaking of large coal, and work has commenced on new problems connected with the treatment of fine coal. The study of the carbonization and complete gasification of coal has continued, and progress has been made in the production of smokeless domestic fuel. The gas produced has been used for synthesis of liquid hydrocarbons by catalytic action. The pulverized-fuel burners and the feed methods elaborated at the Fuel Research Station have continued to give satisfactory performance in industry, and methods for the removal of grit and sulphur from the flue-gases are being studied. Attention is also being directed to the use of pulverized coal in internal-combustion engines, and research is being carried out on the resultant wear of cylinder-linings. Catalysts suitable for the hydrogenation of tar and tar-distillates are being investigated, and as a result it has been found possible to produce either the ordinary type of motor-spirit or a spirit rich in saturated hydrocarbons, whilst work on new catalysts is directed to the ultimate production of lubricating oils. Another method of attack has been to synthesize hydrocarbons by the treatment of mixtures of carbon monoxide and hydrogen with catalysts to produce motor-spirit, diesel oil, and a range of lubricating oils. Further investigation has been made into the constitution of coal, and in particular the effect of certain reagents upon coal has been studied.

RESEARCH IN ENGINEERING AT OXFORD UNIVERSITY, OCTOBER, 1937.

The following notes relate to researches in progress in the Department of Engineering Science at Oxford University (Professor of Engineering Science : R. V. Southwell, M.A., F.R.S.).

Civil and Mechanical.

An impact-testing machine has been developed, consisting essentially of a ballistic balance, both hammer and anvil being suspended by steel wires. In this way it is possible to check the measurements by consideration of momentum and to form an energy balance-sheet from which the work done in fracture can be computed. A method of loading has been evolved which employs a standard cylindrical

test-specimen having a central annular V-notch and subjected to pure bending. With a smaller machine of the same type two further check tests can be made on specimens prepared from the broken halves of the original test-piece. This enables a study to be made of the laws of fracture and scale-effect.[1]

The mathematically-determinate nature of pulsating viscous flow in a cylindrical tube is utilized in the "oscillation viscometer," an instrument devised for the accurate determination of the viscosity of oils and other liquids. The ratio of the amplitudes of oscillation of columns of the liquid and of mercury in U-tubes connected in parallel is a function of the viscosity of the liquid.

An investigation is being made of the flow of steam through a convergent–divergent nozzle. The pressure-distribution along the nozzle has been studied and measurements made of the pressure-rise occurring at the section where condensation of the steam commences.

An analogous research in hydraulics is a study of the formation of standing waves in the divergent portion of a venturi flume. The discharge of such a flume under free-flowing and drowned conditions has been studied, and the curvature of the stream-lines has been shown to modify the pressure-distribution on the bottom.

Another hydraulic research concerns the discharge over circular weirs and includes a study of the maximum head over the weir which can be attained without the initiation of vortex motion.

A method of stress-calculation in frameworks has been developed, termed the "method of systematic relaxation." Applied in the first place to structures with members of uniform section, it has been extended to members of variable section under variable loading, and the possibility of its extension to dynamic and other problems is being explored.

Electrical Engineering.

A fundamental research is being conducted into the mechanism of energy-loss in dielectrics exposed to an alternating field. Compounds of simple molecular structure are being studied. Work on solid solutions of paraffin waxes and esters has been completed, and work on compounds with a naphthalene matrix is in progress.

Researches have been in progress for some years on problems connected with wireless transmission and reception. One such problem concerns the stability of frequency of wireless transmitters

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[1] For further information see the Paper "Impact Testing from a Physical Standpoint," read at the Joint Committee of Technical Institutions on Materials and Their Testing, on 29 Oct., 1937, at Manchester.

in so far as it is affected by electrical phenomena, but at present this work is in abeyance until the complementary thermal problem which is being studied at the National Physical Laboratory has reached a more advanced stage of solution. A study has been made of background noise in thermionic amplifiers: the experimental side of this research, which is still in progress, has recently been transferred to Manchester University, where Dr. F. C. Williams (who has been engaged in it) has recently accepted a lectureship.

NOTES ON RESEARCH PUBLICATIONS.

Measurement and Measuring and Recording Instruments.

A memorandum has been published by the Ordnance Survey on the magneto-theodolite. An instrument for measuring the thickness of coatings of metals is described in *J. Sci. Instruments*, **14,** *341.* A method of measuring and an apparatus for determining the elastic behaviour of elastic substances is described in *Physica*, *1937*, **4,** *221*, and a method of measuring the elastic constants of solids by means of supersonic waves is given in *Ver. deu. Ing.*, **81,** *878.* The measurement of strains on the surfaces of structural elements by the use of polarized light, thus dispensing with the use of models, is described in *Ver. deu. Ing.*, **81,** *803.* The compensation of strain-gauges for vibration and impact by suitable adjustment of the ratio of inertia to rigidity is dealt with in *U.S. Bur. Standards J. Research*, **18,** *723.*

Engineering Materials: Properties and Testing.

Tests to determine the effect of pressure on the modulus of rigidity of several metals and glasses are discussed in *Physics*, **8,** *129.*

Timber.

Forest Products Research Record No. 21, Growth and Structure of Wood, has been issued by the Department of Scientific and Industrial Research. A new meter for the determination of the moisture-content of timber by electrical capacity-effects and its application is described in *J. Council for Scientific and Industrial Research* (*Australia*) *1937*, **10,** *235.*

Bricks, Cement, and Concrete.

The wick test for efflorescence of building brick is described in

The figure in heavy type is the number of the Volume; that in brackets the number of the Part; and that in italic type the number of the Page.

U.S. Bur. Standards J. Research, **19,** *105.* The relation of pore-size of bricks to their resistance to disintegration by freezing is discussed in *U.S. Tech. News Bull.* (*243*) *73.*

The effect of the chemical composition of Portland cement on its mechanical strength is discussed in *Tsement*, **5** (*2*) *22.* Pozzuolanas and pozzuolanic cements are dealt with in *La Chimica e l'Industria*, **19,** *1.* Sea-water cements are discussed in *Zement*, **26,** *213.* The chemical resistance of Portland pozzuolana cements is dealt with in *Trans. Leningrad Industrial Inst., 1936, Physical and Mathematical Section No. 2* (*9*) *16.*

The following researches deal with the resistance of cements: The durability of Portland pozzuolana cements in air and in salt-solutions as influenced by an admixture of calcium chloride, *Trans. Leningrad Industrial Inst. 1936, Physical and Mathematical section No. 2* (*9*) *3*, and on *p. 16*, The chemical resistance of Portland-pozzuolana cements ; An investigation of the resistance of Portland cements to the action of magnesium-sulphate solution, *Zement*, **26,** *210 ;* The stability of pozzuolanic and Portland cements in solutions of magnesium sulphate and chloride, *Tsement*, **5** (*1*) *12.* A short account of mineral sulphates and their influence on concrete design and construction is given in *Paper No. 5* of the *Public Works, Roads, and Transport Congress, 1937.* The following American researches have been noted : *J. Am. Concr. Inst.*, **9,** *25*, Length-changes of cement paste in relation to combined water ; *p. 45*, Measurement of the moisture-content of concrete ; *p. 65*, A simple test for water-permeability of concrete. The influence of moulding pressure on the compressive strength of concrete is discussed in *Concr. & Constr. Eng.*, **32,** *121.* A Paper on the size-grading of sand by wind is included in *Proc. Roy. Soc. Series A*, **163,** *250.*

Metals.

The effect of over-stressing and under-stressing of carbon steels in fatigue is discussed in *Engineering*, **143,** *620* and *676.* The plastic behaviour of metals in the strain-hardening range is dealt with in *Physics*, **8,** *205. British Standards Specification No. 729* has been issued, giving a standard method for testing the zinc coating of galvanized articles other than wire (copper-sulphate test, and visual examination). The following researches on corrosion have been noted : The influence of films on the incipient corrosion of iron, *Paint*, **7,** *179 ;* Initial corrosion-rate of mild steel—influence of the cation, *Ind. Eng. Chem.*, **29,** *814* and on *p. 1087*, Corrosion probability. Soil-corrosion testing is dealt with in *U.S. Nat. Bur. Stands. Tech. News Bull., 1937* (*242*), *61.*

Engineering Materials: Production, Manufacture, and Preservation.

Results of experiments on humid-aging of fly-ash brick whereby certain disadvantages are eliminated are given in *Ind. Eng. Chem.*, **29,** *427*

The kinetics of the carbonation of artificial lime-sand stone are discussed in *J. of Applied Chem.* (U.S.S.R.), **10,** *290.* The workability of concrete is discussed in the following: Study of workability of concrete in reinforced-concrete construction, *Ann. Inst. Tech. Bâtiment*, **2** (*4*) *3*; and on *p. 47*, Note on the workability and the compaction of concrete with rounded aggregates; The workability of concrete and mortars, *Eng. News-Rec.*, **119,** *17*; A new method of measuring the workability of concrete, *Ann. Inst. Tech. Bâtiment*, **2** (*1*) *48.* A vibrograph for measuring the transmission of vibration through fresh concrete is described in *U.S. Nat. Bur. Stands. Tech. News Bull.*, *1937* (*244*), *86.* The moist curing of concrete is discussed in *Eng. News-Record*, **119,** *630.*

The preparation of steelwork for painting is dealt with in *Ind. Eng. Chem.*, **7,** *222.*

Structures.

Mass Structures.

Soil-sampling and core-drilling in tidal water for foundation exploration is described in *Eng. News-Record*, **119** (*16*) *635.* *Paper No. 12* of the *Public Works, Roads, and Transport Congress*, *1937*, discusses methods of dealing with bridge-foundations in bad ground or under water. A symposium on the practical application of soil mechanics is contained in *Proc. Am. Soc. Civ. Engineers*, **63,** *1303.* The subsoil coefficient is shown to vary with the size of area loaded and with the specific pressure in *Annali dei Lavori Pubblici*, *1937*, **75** (*1*) *13.* A Paper on the stability of earth dams under the action of constant or varying pressure is contained in *Permanent International Association of Navigation Congresses No. 24*, *81.* The design of rock-fill dams, with particular reference to American practice, is discussed in *Proc. Am. Soc. Civ. Engineers*, **63,** *1451.* A method of compacting stone filling inside caissons by the use of a pile-driver is described in *Tek. Tidskrift*, **67** (*26*) *Väg- och Vattenbyggnadskonst* (*6*), *68.* A method of calculation for the foundations of machines under the influence of periodic vertical forces is given in *Science et Industrie* (*Mécanique*), **21** (*274*) *225.*

Framed Structures.

A solution of the elastic-curve equation, $M = EI\frac{d^2y}{dx^2}$, derived from the shear diagram, is described in *Rensselaer Polytechnic Inst., Eng. and Science Series, Bull. 54*. A mathematical solution for the elastic stability of a corrugated plate under a shearing force is given in *Proc. Cambridge Phil. Soc.*, **33**, *459*. In *Univ. Illinois Eng. Expt. Stn. Bull. 295*, tests are given of thin hemispherical shells subjected to internal hydrostatic pressure. Tests of steel columns, thin cylindrical shells, laced channels, and angles, in which the wrinkling stress is found, are given in *Univ. Illinois Eng. Expt. Stn. Bull. 292*. The combined effect of corrosion and stress-concentration at holes and fillets in steel specimens subjected to reversed torsional stresses is discussed in *Univ. Illinois Eng. Expt. Stn. Bull. 293*. A theoretical study of wires under tension and transverse forces, with special reference to the failure of wire ropes, is given in *Phil. Mag.*, **23**, *1114*. The calculation of steel portals, taking account of plastic deformation, is given in *Ossature Métallique*, **10**, *479*. Calculations for cylindrical roofs of elliptical form are given in *Génie Civil*, **111**, *323*.

The behaviour of rectangular concrete section under torsion is discussed in *J. Am. Concr. Inst.*, **9**, *1*. Researches on reinforced concrete include: Reinforced-concrete disks or wall-like girders, i.e. construction of walls without supporting girders, *Proc. South African Soc. Civil Engineers, 1937, p. 121;* Important economies in design in relation to elastic properties of concrete, with particular reference to reinforcement, *Cemento armato, 1937*, **34**, *122;* Regulations of the German Reinforced Concrete Committee, a revision of the *1932* regulations, *Deutscher Ausschuss für Eisenbeton, Berlin, 1937;* The shrinkage of reinforced concrete, *Ann. Trav. Pub. de Belgique*, **90**, *155;* Pre-stressed reinforced concrete and its possibilities for bridge construction, *Proc. Am. Soc. Civ. Engineers*, **63**, *1277*, and in the same journal, *p. 1475*, Design of reinforced concrete in torsion.

Confirmation by model experiments of a method of minimizing the seismic vibrations of a structure is described in *Bull. Earthquake Research Inst., Tokyo Imperial Univ.*, **25**, *598*.

Transformation, Transmission, and Distribution of Energy.

The following researches on fuel have been noted: Studies of our knowledge of coal selection for steam-generating equipment, *Mechanical Engineering*, **59**, *829;* Gas for commercial and industrial uses, *Paper No. 7, Public Works, Roads, and Transport Congress, 1937;* Physical and chemical factors in the ignition and combustion

of carburetted mixtures, *Science et Industrie* (*Mécanique*), **21** (*274*) *220*; Research in relation to the motor-vehicle—Fuels and lubricants, *J. Inst. Petroleum Technologists*, **23,** *575*, and on *p. 602*, The determination on a laboratory scale of the ignitability of diesel oils. The penetration of oil-sprays is discussed in *Bull. No. 46*, *Pennsylvania State College*.

The following researches dealing with transmission of energy have been noted: Power-transmission by belt, rope, chain, and gearing, *Trans. Inst. Engineers-in-Charge*, **43,** *66*; The gas-impregnated cable, *J. Inst. Elec. Engineers*, **81,** *625*; and the *17th Annual Report* of the Electricity Commissioners.

Mechanical Processes, Appliances, and Apparatus.

The following researches on welding have been noted: Fusion-welded pressure-vessels, *Welding Industry*, **5,** *353*; in the *Welding Journal*, **16** (*9*), *Research Supplement*, *p. 4*, Temperature-distribution during welding—A review of the literature to 1 January, 1937; *p. 11*, Fusion welding of wrought iron; *p. 23*, Effect of total carbon and manganese on the mechanical properties and structure of welded joints in plain low-carbon steel; and in **16** (*10*), *Research Supplement*, *p. 2*, Effect of welded top angles on beam-column connexions; *p. 9*, Spot-welding characteristics of some copper-base alloys; *p. 19*, X-ray methods of studying stress-relief in welds; *p. 23*, Fatigue tests of butt welds in structural plates; *p. 27*, Welded girders with inclined stiffeners; *p. 30*, The welding of copper; *p. 41*, Static and impact tensile properties of some welds at ordinary and low temperatures; *p. 47*, An alternating-current non-destructive test for welded seams; *p. 50*, Studies of the oxy-acetylene cutting process; *p. 53*, The heat effect in welding—a review of the literature to January, *1937*; *p. 71*, Discussion on fusion welding of wrought iron. The sleeve electrode for the arc-welding of copper is discussed in *Elektroschweissung*, **7,** *161*, and in *Welding Industry*, **5,** *63*. Researches into lubrication include tests of bearing metals and bearings under dynamic loading, *Ver. deu. Ing.*, **81,** *1245*, and the following in *Science et Industrie* (*Mécanique*), **21** (*274*), *p. 203*, influence of the state of surfaces on the friction forces and the adjustment with shaking; *p. 207*, New processes for measuring the state of worn surfaces; *p. 209*, Relation between the state of surfaces and the dispersion of light; *p. 211*, Effect of the state on resistance to fatigue; *p. 214*, Influence of the state on the adjustment to pressure.

Specialized Engineering Practice.

Transport.

The presidential address of Sir Alexander Gibb to the Institute

of Transport, on Engineering Limitations and Transport Ideals, is given in *J. Inst. Transport*, **19**, *7*. The following researches in connexion with roads have been noted: *Dept. of Scientific & Industrial Research, Road Research Tech. Paper No. 2*, Studies in road friction II: An analysis of the factors affecting measurement; *Public Works, Roads, and Transport Congress, 1937, Paper No. 3*, Materials used in modern road construction, and *Paper No. 8*, Modern road tars. The proceedings of the 23rd Annual Road School are given in *Eng. Bulletin Purdue University Extension Series No. 39*. A study of the passing of vehicles on highways is made in *U.S. Dept. Agric. J. Highway Res.*, **18**, *121*. Principles of soil-stabilized road construction are discussed in *Roads*, **15**, *230*. Articles on the use of salt in road stabilization are contained in *Can. Eng.*, **73** (*4*) *5* and in *Am. Inst. of Mining and Metall. Engrs. Tech. Publication No. 721*. The vibration of concrete in road construction is discussed in *Civil Eng. and Pub. Works Rev.*, **32**, *204*. The following articles in connexion with bituminous surfacings have been noted: Viscosities of liquid-solid systems. Influence of dispersed particles: *Ind. Eng. Chem.*, **29**, *489*; Method for testing the permeability of bituminous road surfacings, *Strasse*, **4**, *474*; Cotton fabrics for bituminous-surfaced roads, issued by the *U.S. Dept. Agric.* 1936; and a pamphlet issued by the *Cotton-Textile Inst. Inc. New York, 1936*, Cotton fabric-reinforced roadways and runways.

In connexion with Railways: A simplified process for the theoretical investigation of rail-creep is given in *Organ für die Fortschritte des Eisenbahnwesens*, **20**, *369*, and tests on strength properties of chilled car-wheels are given in *Univ. Ill. Eng. Expt. Stn. Bull. 294*.

Researches on marine transport include: Ship-propulsion under adverse weather conditions, *Trans. N.-E. Coast Inst. of Engrs. & Shipbuilders*, **53**, *55*; Design for economy in ship-propulsion, *Trans. Inst. Marine Engrs.*, *49* (*1*); Re-analysis of William Froude's experiments on surface friction and their extension in the light of recent developments, *Trans. Inst. Naval Architects*, **79**, *120*; The effect of shape of bow on ship resistance, Part 1, *Trans. Inst. Naval Architects*, **79**, *188*. Experimental fluid mechanics—a study of the hydrodynamic tunnel from the point of view of motion in two directions, is given in *Comptes Rendus de l'Académie des Sciences*, **205**, *714*. Apparatus for the measurement of wave-pressures is described in *Rev. Gén de l'Hydraulique*, **3**, *189*. A study by scale models of the removal of silt in front of a lock-gate by suitable flushing arrangements and verification of the results obtained, *Science et Industrie* (*Travaux*), **21** (*58*) *423*. The presidential address of Dr. Stephen J. Pigott, on Three Score Years of Development in Marine Engineering, is given in *Trans. Inst. Marine Engrs.*, **49**, *179*.

In *J. Roy. Aero. Soc. 41,* the following articles have been noted: *p. 975,* Control surface and wing stability problems; *p. 997,* Power plant trends; *p. 1042,* Design of multi-spar wings. *Paper No. 21* of the *Public Works, Roads and Transport Congress, 1937,* deals with the construction of municipal aerodromes. The following Aeronautical Research Committee *Reports and Memoranda* have been noted: *No. 1758,* Vibration of airscrew-blades with particular reference to their response to harmonic torque impulses in the drive; *No. 1770,* Behaviour of a pitot tube in a transverse total-pressure gradient; *No. 1775,* Experimental determination of the bending actions induced by axial end constraints in a rectangular tube in torsion; *No. 1776,* Note on the directional stability of seaplanes on the water; *No. 1777,* Effect of differences of form on the porpoising characteristics of two flying-boats; *No. 1778,* Note on the standardization of pitot-static head position on monoplanes; *No. 1780,* Diffusion of concentrated loads into monocoque structures.

The following National Advisory Committee for Aeronautics *Reports* have been noted: *No. 605,* Resumé and analysis of N.A.C.A. lateral control research; *No. 606,* Electrical thermometers for aircraft; *No. 609,* Experimental investigation of wind-tunnel interference on the downwash behind an airfoil.

Water-Supply, Water-Power, and Sewage-Disposal.

Methods of locating salt-water leaks in water wells are described in *U.S. Dept. of the Interior, Geological Survey, Water-Supply Paper No. 796-A. Paper No. 19* of the *Public Works, Roads, and Transport Congress, 1937,* deals with the possibilities of the lower greensand as a source of water-supply for Greater London, and *Paper No. 20* with weather and water-supply. A study of standard and increment methods of measuring stream flow, namely by current-meter and by power-plant discharges corresponding to increments of load, is contained in *Engineering Journal* (*Canada*), **20,** *781.* Measurement of debris-laden stream-flow with critical-depth flumes is discussed in *Proc. Am. Soc. Civ. Engineers,* **63,** *1259.* A note on the coefficient of discharge of automatic siphon spillways is given in *Annales des Ponts et Chaussées,* **107**-*i, 733,* and on *p. 805* the torsion of flashboards and trestles in flashboard dams is discussed. The action of ice on engineering constructions and on the mechanical parts of hydro-electric installations in running waters is discussed in *Rev. Gén. de l'Electricité,* **42,** *555.* Experiments on a small-scale model of a sector weir are given in *Rev. Gén. de l'Hydraulique,* **3** (*16*) *193.* Underwriters' tests of transite pipe are given in *J. New England Waterworks Assoc.,* **51,** *282,* and on *p. 277* is an article on the electrical grounding of water-pipes. Tests with "sinterit" for staunching socket-joints in water-mains are given in *Gas-*

und Wasserfach, **42,** *763*. Steel stresses in reinforced-concrete pipes are discussed in *Eng. News-Record*, **119** (*15*), *597*. The calculation of water-hammer in a pipe with unique characteristics, *i.e.* one in which the diameter and thickness are constant, is explained in *Rev. Univ. des Mines et de la Métallurgie*, **13,** *415*. The solution of transmission problems of a water system is discussed in *Proc. Am. Soc. Civ. Engineers*, **63,** *1511*. The proceedings of the 11th Annual Conference on Water Purification are contained in *West Virginia Univ. Eng. Expt. Stn. Tech. Bull. No. 9*. The following have been noted in *J. Am. Waterworks Assoc.*, **29;** *p. 1472*, Zeolites and organic exchange filters ; *p. 1591*, Some notes on sand filtration ; *p. 1603*, Experiences with activated carbon at Hammond, Indiana.

The following papers on sewage-disposal at the Public Works, Roads, and Transport Congress, 1937, have been noted : *Paper No. 2*, The occurrence of dilute sewage and its rational treatment ; *Paper No. 17*, The design of sewers ; *Paper No. 18*, Some considerations in the design of sewage and storm-water pumping-stations ; *Paper No. 22*, The treatment of waste waters from dairies ; *Paper No. 23*, Some notes on the ventilation of percolation filters ; *Paper No. 27*, A contribution to the literature relating to the activated-sludge process. *British Standard Specification No. 540*, for salt-glazed glass-enamelled fireclay pipes, has appeared. Aeration tanks for activated-sludge plants are discussed in *Proc. Am. Soc. Civil Engineers*, **63,** *1535*. The adaptation of gas-engines to sewage-sludge gas is dealt with in *Mechanical Engineering*, **59,** *835*.

Mining.

A solution of the problem of heat-flow in an infinite solid bounded internally by a cylinder—a problem of interest in connexion with the cooling of deep mines—is given in *Physics*, **8,** *441*. Surface refrigeration compared with underground refrigeration for mine-air cooling on the Witwatersrand goldfields is discussed in *J. South African Inst. Engineers*, **36,** *42*. Notes on an instrument designed to record continuously the amount of dust in air are given in *J. Chemical, Metallurgical, and Mining Soc. of S. Africa*, **38,** *75*. Notes on the effect of dusts on lighting in mines are given in *Trans. Inst. Mining Engineers*, **93,** *378 ;* in **94,** *1*, is the Interim Report of the Committee on shot-firing and its alternatives ; on *p. 93*, Co-ordination of theories of gravity separation ; and on *p. 114*, The law of motion of particles in a fluid.

Lighting, Heating, and Acoustics.

Problems in building illumination are discussed in *Univ. Illinois Eng. Expt. Stn. Bull.* ,**34,** *No. 29*.

The coefficient of heat-transfer for vertical surfaces in still air

is discussed in *Canadian J. Research, Section A*, **15,** *109*, and research on heat-transmission phenomena in the boundary layer of air is described in *Trans. Soc. Mechanical Engineers, Japan*, **2,** *367* (English summary given). Gas-fires and comfort are discussed in *Gas Journal*, **219,** *52*. The performance of fin-tube units for air cooling and de-humidifying is dealt with in *Heating, Piping*, **9,** *379*.

Researches on noise include: Sound-absorption by solid bodies, *Physikalische Zeitschrift der Sowietunion*, **11,** *18*; Noise-reduction in buildings, *Gesundheits Ing.*, **60,** *616*; The noise nuisance and sound insulation, *Beton*, **3** (*2*) *1*.

Telegraphy and Telephony.

A Paper on the radiation-field of a perfectly-conducting base-insulated cylindrical antenna over a perfectly-conducting plane earth, and the calculation of radiation-resistance and reactance, is given in *Phil. Trans. Roy. Soc. Series A*, **236,** *381*. The following articles appear in *J. Sci. Instruments*, **14**; *p. 325*, High-gain low-frequency amplifiers; *p. 335*, The vibration magnetometer; *p. 339*, A note on the calibration of audio-frequency oscillators. In *Zeitschrift für Technische Physik*, **10,** *312*, an apparatus for frequency analysis by the search-tone method with two intermediate frequencies and logarithmic indicator is described. In *Hochfrequenztechnik und Elektroakustik*, **50,** the following have been noted: *p. 96*, A grid-controlled magnetic-field tube with a cathode outside the anode-cylinder; *p. 98*, Damping measurement on metre-waves; *p. 121*, Echo measurements in the ionosphere. The following researches have been noted in *J. Inst. Elec. Engineers*, **81**; *p. 573*, Modern systems of multi-channel telephony on cables; *p. 658*, The dependence of the inter-electrode capacitances of valves upon the operating conditions; *p. 667*, The apparent inter-electrode capacitance of a planar diode; *p. 676*, An improved medium-wave Adcock direction-finder; *p. 682*, A short-wave Adcock direction-finder.

MISCELLANEOUS.

The principle of similarity—the fundamental conditions of similarity and identity in the mechanical sciences are examined in *J. Inst. Engineers, Australia*, **9,** *341*. *A Summary of Progress of the Geological Survey of Great Britain and the Museum of Practical Geology for the year 1936, Part 1*, has been published. Hydro-technical methods in the prevention of malaria are discussed in *J. Roy. Sanitary Inst.*, **58,** *345*.

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